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**LECTURES ON  
STEEL AND ITS TREATMENT**



# LECTURES ON STEEL AND ITS TREATMENT

*By*

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## FOREWORD

FOR many years it has been the ambition of the writer to put into printed form the substance of this series of six lectures, which are in part the result of many years of intensive study of the properties of iron and steel.

During his earlier days the author served his apprenticeship as a blacksmith. The more he worked with wrought iron and steel the more interested he became in the characteristics of these materials. His curiosity was thoroughly whetted and his keenest desire to learn the "why" of all the things that happened to steel during forging, hardening, and tempering was aroused.

Limited by a somewhat meagre education the road to the end was a long one. In the course of events the writer became an instructor in forging in one of the leading engineering colleges. While so engaged, he had the opportunity of studying the underlying reasons for changes in grain size, the action and reaction of metal under the forging hammer, and in its subsequent heat treatment. As the shop work progressed the author devised means of illustrating the underlying theories to his students. Many of these illustrations are included in these lectures.

In the past few years he has been giving the lectures, essentially as contained in this book, to industrial groups throughout the State of Indiana, as a part of the extension services of Purdue University. For the past two years a portion of each year has been spent in presenting these lectures in a National way, before groups organized under the auspices of the American Society for Steel Treating and Purdue University.

It is hoped that this material will lead those interested in the processing and treatment of metal to a better understanding of the subject. It is also hoped that the reader will find the time and desire to peruse the literature on this subject, as there is a wealth of information to be had in almost any library.

The author is indebted to the following for their cooperation in allowing the reproduction of photographs and for helpful suggestions: R. G. Guthrie; H. J. French; O. Z. Klopsch; Dr. Zay Jeffries; R. S. Archer; Dr. Albert Sauveur; F. T. Sisco; H. B. Knowlton; R. S. MacPherran; the Colonial Steel Company; the Bethlehem Steel Company; *Heat Treating and Forging*; George J. Hagan Company; Leeds and Northrup Company; Stanley P. Rockwell Company; Bureau of Standards; Brown Instrument Company and the American Society for Steel Treating.

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September, 1928

JOHN F. KELLER.



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## LECTURE I



# LECTURES ON STEEL AND ITS TREATMENT

## LECTURE I

### MELTING THE STEEL AND WORKING THE INGOT

#### *Foreword*

THE object of the author in the preparation of the subject matter of these six lectures dealing with STEEL AND ITS TREATMENT is to assist men in the metal trade industries to a better understanding of the basic principles that underlie the various processes of producing iron and steel tools and machinery.

During the past several years it has been a very pleasant part of the author's daily work to collect certain information concerning the basic principles of the manufacture and treatment of iron and steel parts and tools, and so organize it that it may be presented to men in such form, that in a reasonable length of time they may acquire a fairly definite understanding and insight into the fundamentals of iron and steel. A great deal has been written on the subject, but in the author's opinion much of this material is presented in such a highly scientific style that it is difficult for the non-technical man to obtain a concrete picture of the ideas involved. Therefore it is the purpose of this work to present certain information, charts and illustrations that may render the subject matter more comprehensible.

For several years the writer has been a field man or steel specialist, furnishing advisory service to the metal trade industries of the State of Indiana. Numerous questions have constantly been presented concerning the cause of failures of metals in service. Some of these questions were simple in nature and could be answered without much investigation, but many were complex and necessitated considerable investigation before an intelligent answer could be submitted. Many of these questions and their answers form the basis of these lectures.

Before taking up the subject matter in detail let us devote a few words to general conditions that have been observed by the writer, particularly as to the many causes leading to the ineffi-

ciency or failure of tools and machinery parts in service. We find that the human element plays a very important part in the development of efficient material, as well as in failures. Scientifically treated iron and steel may be likened to the trained man in any vocation of life and particularly to the trained athlete who undergoes a series of strenuous mental and physical exercises in order to develop quick thinking and trained muscles to endure fatigue.

A simple illustration is to select two men of good health to run a foot race of 100 yards, the men being apparently alike in every respect except that one is trained for the purpose and the other is not. The result of such a contest would be inevitable failure of the untrained man. Likewise, the failure of unscientifically treated metal may be largely traced to an inferior knowledge of the basic principles or essential factors necessary to impart fatigue resistance to such metal.

Iron and steel parts of machinery may be good, bad or indifferent even when made of similar material, depending largely upon the base metal, the process of manufacture, and final heat treatment. This variable quality of metal may be likened to the many variables found in the making of bread, pies, and cakes baked by an untrained housewife. Most all of us have had occasion to sample food made by untrained hands. Occasionally such unsatisfactory material is "slipped in," even by those who are scientifically trained. And why? Because of the uncertainty of the human element.

In the trades, men usually learn their vocation by observation and practice and from such information as may be collected from men who have previously learned their trade under similar conditions. Probably few of these men ever learn their trade or vocation under a technically trained teacher who is capable of presenting the basic principles as to the "why" for certain operations and results. One may readily see the cause of many misleading statements that have been handed down from past generations. It is a known fact that the ancient metal workers were required to take an oath of secrecy not to divulge the secrets of their trade or vocation except to those of blood relationship. Some of this ancient condition of affairs exists today. However, due to metallurgical science and investigation by highly trained men and through the publication of reliable data, many of the charac-

teristics of steel, formerly mysterious to the average metal worker, are now common knowledge. This is particularly true in "procedure controlled plants" which employ technically trained men to guide and inspect the processes of manufacture.

One may readily grasp the "why" for the differences in the efficiency of similar metal parts, fabricated and heat treated under procedure control, and those tools made by rule of thumb practices. The materials and parts of machinery which are the products of those who learned their vocation by rule of thumb are often analogous to the products of the untrained cook.

One of the erroneous statements accepted by many users of steel is the idea that iron and steel can crystallize in service, and because of this crystalline condition, fail in service. Logical reasoning should easily convince one that such development cannot occur in metal in the cold state, due to its rigidity. In reality, the seemingly large grains in the fracture are jagged edges of the irregular path of the fracture. The metal is composed of countless small grains that cannot usually be seen without the aid of a microscope. With this brief touch of the background we will now trace the making of steel.

### *Making Steel*

The subject matter in this lecture is arranged largely in sequence of operation as the product passes through production, with emphasis on many causes of defects. The sequence will of necessity be broken occasionally by the explanation of certain phenomena.

### *History*

History records but little information concerning the ancient methods of making iron and steel weapons and tools. In those days, as in modern times, iron was the base of all steel, but with carbon the most important element combined with the iron, whereas other elements have been added in more recent times in the manufacture of steel. Historians point out that meteoric iron was the first source of supply but the ancient worshipers fearing that meteorites were a message of warning from the Heavens, failed to utilize this valuable material. Commodore Peary reported in

his trip to the North that the Eskimos revered the meteorite. Nevertheless they chipped off corners for spear points.

No one knows exactly how iron ore was discovered, but a plausible picture will be set forth. Probably the first real discovery of iron ore upon the earth's surface was due to an intense fire in a wooded section adjacent to a hillside. The wind blowing strongly in the proper direction drove the intense flame against the hillside and, so to speak, melted the rock into a liquid which ran in rivulets into the valley. The men were curious, examined the solidified mass when cold and pounding it with a stone, found that it would not break or crumble.

They then tried heating and pounding it between rocks (the only form of tools available). The metal was plastic and capable of being formed into different shapes. Primitive men began to form various kinds of crude weapons with which to defend themselves. Later they developed tools to till the soil and hew timber. Being men of at least some reasoning power, they tried to duplicate the forest fire by building a clay furnace in the hillside, using the newly discovered iron ore and charcoal from the burnt timbers and a natural draft to fan the flame. (Two pictures taken in Africa a few years ago were shown to the writer last September and seemed to confirm this statement). This type of furnace produced a pasty ball of iron, similar to our present day wrought iron.

Another accident may have occurred in an unusually heavy wind storm while a charge of ore was being smelted in the crude furnace. The flame, fanned to an intense heat, partially carburized (adding carbon to the soft pasty iron) the product. A lump of the heated, solidified mass was thrown into a running stream. When cold, they discovered the metal to be unusually hard by testing it for hardness with stone hammers for they had no such thing as files or modern hardness testing devices.

It was the assumption in those days that the metal at high temperature took up some fatty matter or other product of the fuel, men little dreaming then that at that high temperature it was the pure carbon from charcoal that combined with iron.

Duplication of such carburization could only occur when an intense wind was blowing. They therefore decided to reproduce this condition in a small concentrated fire, similar to our present forge fire and by this process attempted to carburize the points

of their weapons and tools. For many years this was the common process of manufacture. The ancients learned two things: (1) how to carburize iron and (2) when so carburized, if quenched in water at a red heat, such metal would become hard.

This description may not suffice to give a clear conception of the process, and show why carbon of the fuel should impart such a distinct hardness to iron. Let us go back to the middle ages and attempt to trace the manufacture of the wonderful Damascus swords which were prize possessions of royalty in the olden days. The following is taken from an article by Dr. J. W. Richards, *TRANSACTIONS of the American Society for Steel Treating*, Volume I, page 94, "A piece of iron about six inches long and two inches wide was taken, doubled over on itself and then welded out until it was the original length.

"That operation of doubling it, welding it and working it out was repeated fifteen times. At the end of that time three pieces of similar sizes were thus worked in the same way. Those three pieces placed one on top of the other were then worked out into bars six inches long, two inches wide and this bar was again split in two and welded five times. With a skilled workman getting about twenty cents a day, that treatment did not cost much in those days, and you can figure out from that, there are about four million layers in that steel blade, and really, I believe that this tremendous amount of working and the tremendous number of layers account in a large measure for the beauty and strength of those old swords. It is related of Richard Coeur de Leon, the English king, that when he was in Palestine he had with him his big two-handed sword when Saladin, the Saracen emperor, met him. They were bragging about their swords and Richard ordered them to put down an iron bar about an inch in diameter. He whirled his sword around his head and came down and cut the steel bar in two. Some feats of that sort were really done with those magnificent old two-edged swords about five feet long with an immense handle for two hands. Saladin took out his curved scimitar and called an attendant who threw a lady's veil into the air; Saladin cut it in two with his scimitar as it was floating in the air. Something like that can be done with those magnificent swords of Damascus."

*Ancient Method of Carburizing*

The ancient method of carburizing iron was by melting the iron or heating it to a high temperature in contact with carbonaceous fuel. Iron, at the proper temperature, has a great affinity for carbon. In making Damascus swords, carburizing was accomplished by heating to a welding heat in contact with the carbonaceous fuel. When a piece of wrought iron is heated to a welding heat in contact with carbonaceous fuel, such as charcoal, coal or coke, its surface will absorb a certain amount of carbon from the fuel. In making the swords, this metal was welded, drawn and doubled over and welded many hundreds of times and each time a portion of the metal in contact with the fuel at a white heat absorbed some carbon. This is the reason for the statement of Dr. Richards that perhaps there were several million layers of steel in that tough blade.

If one wishes to attempt the manufacture of a similar type of metal, it may be done in a more simple way by carburizing a large number of rods about a quarter of an inch square in a regular carburizing furnace, welding them together, doubling them over a few times, hammering them out, then finally twisting them, and doubling and welding again and again. From this operation one may obtain a structure similar to the structure of a Damascus blade. We may now see one of the reasons "why" the average weld from a forge fire or some welds from an oxyacetylene torch are hard and unmachinable. It is due to the fact that the material absorbs carbon from the fuel of the forge fire or from an excess of the acetylene gas in the oxyacetylene torch.

*Cementation Process*

The "cementation process" appeared early in the 16th century. Essentially, it consists of heating small pieces of soft iron, each in contact with carbonaceous material, to a carburizing temperature. The soft iron takes up carbon and is carburized. In this condition it is steel, as we shall see. The old cementation furnace as usually described, was a cylindrical muffle furnace, in the bottom of which was placed a quantity of charcoal, then a layer of bars of wrought iron about  $\frac{3}{4}$  to 1 inch thick and 4 to

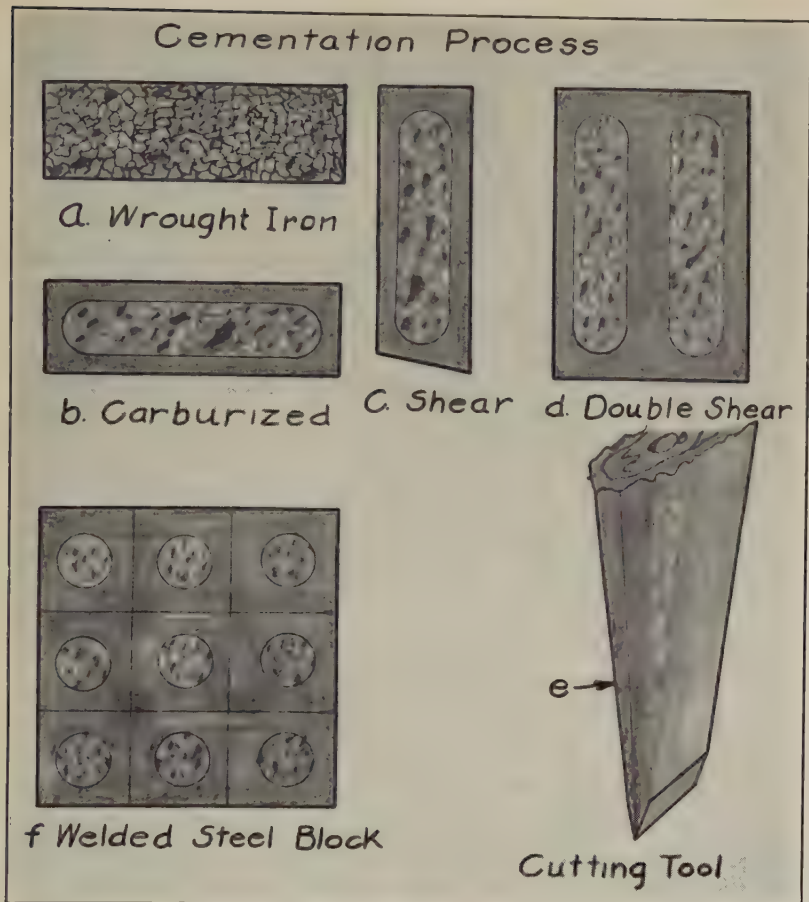


Fig. 1—Cross Sectional Views of a Wrought Iron Bar and Bars of Steel Made by the Cementation Process.

5 inches wide. Full lengths were placed on top of this charcoal so that the bars would not touch one another or the sides of the furnace. More charcoal was piled on, then other layers of wrought iron and so on until the entire furnace was loaded. The muffle was then sealed, heat applied for seven days and nights and the metal allowed to cool for seven days and nights. When removed from the furnace some of the bars were badly blistered and therefore were known as "blister steel." A thick case of high carbon material was formed over the soft center or core.

That the reader may have a clearer conception we present a sketch, Fig. 1, to assist in illustrating the results of the process. "a" represents graphically a cross section of the structure of wrought iron free from carbon. "b" represents a cross section of "a" after the cementation process. The heavy dark section from the surface inward represents steel, or the carburized case. The coarsely crystalline section at the center indicates the original material as indicated at "a". In other words, the carbon has not penetrated to the center of the bar. Such material was formerly used for shear blades as indicated at "c", known as "single shear" steel. If the material was to be used for axes, chisels, or types of tools with center cutting blade, two bars were welded together (known as "double shear" steel), as indicated at "d". This operation brings the two steel surfaces together, and when drawn to the form desired, as indicated at "e", there will be a layer of steel at the center and a layer of steel on the surface. The two soft layers of iron made such tools tough. To make a better grade of steel, these bars were piled and welded, doubled and rewelded in a similar manner to the making of the Damascus sword. Sometimes the original bar was drawn to a square section, then welded, again piled and rewelded again and again, as indicated at "f". In this manner it was impossible to get uniformity of structure throughout the mass.

In 1740 a clock maker named Huntsman conveyed the idea of cutting these cemented bars into small pieces and melting them in a crucible. By this process the carbon thoroughly mixed and combined with the iron. When melted and the metal lay quiet (killed dead), it was poured into a small ingot mold, then drawn into steel bars. This was a secret process and for many years Huntsman made the best tool steel in England. Finally, the secret leaked out. That process was the forerunner of our present method of manufacturing crucible steels. Our present method of carburizing iron and soft steel machine parts in order to develop a hard wearing surface is based upon the cementation method. So much for the crude or "rule of thumb" method of carburizing iron to make steel. But once the iron is thoroughly carburized, what causes decarburization or burning of carbon from the surface of steel?

*The Effect of Oxygen Upon Steel*

The following statement was made by an eminent scientist: "If all of the finished iron and steel parts in the world today were allowed to come into contact with moisture and the free oxygen of the air, there would not be a particle of such metal left in the world 100 years hence." The steel would become oxidized (or rusted) and no longer possess metallic properties.

We see this chemical action of rusting going on around us in our daily walks of life. The metal is slowly oxidizing or burning up in contact with oxygen of the atmosphere, "going back to nature", the oxide of iron, the form of the iron in the original ore. It will be seen that the process of converting the ore to pig

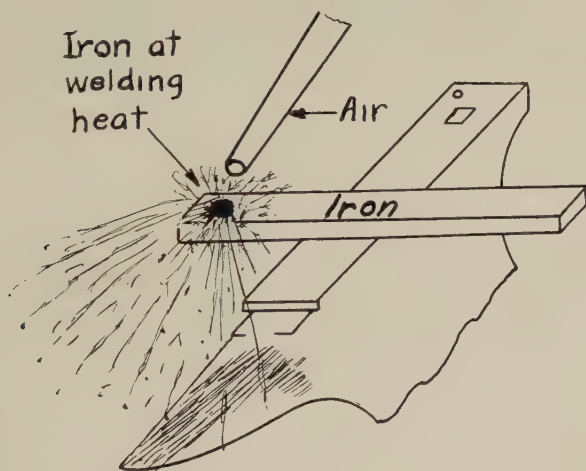


Fig. 2—Sketch Showing the Effect of a Jet of Compressed Air on a Bar of Iron Heated to a Welding Temperature.

iron consists of removing the oxygen that is chemically combined with the iron. Ordinary burning of fuel is the chemical combination of oxygen and carbon, such as in the burning of coal, coke, wood, tar, oils, gas or other carbonaceous fuels. The effect of oxygen on iron can be demonstrated at the reader's leisure by carrying out the experiment shown in Fig. 2. Heat a flat bar of steel to a welding heat, and play a small jet of compressed air on one spot of the hot iron. The oxygen of the air causes the iron to burn and a hole is burned through the bar.

With these points in mind it can be seen that when carbon steel is surrounded with an excess of free oxygen at the proper

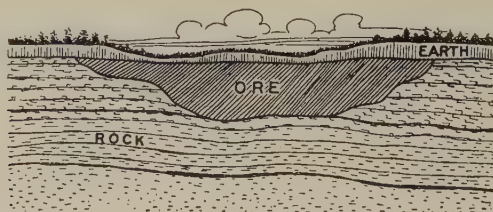


Fig. 3—Typical Cross Section of the Mesabi Ore Bed.

temperature, that the carbon would leave the iron and combine with the oxygen. The oxygen has a great affinity for the carbon. If steel remains in such an atmosphere for quite a length of time, the carbon will be removed for a considerable depth, as clearly demonstrated by the thick skin of decarburized surface on annealed tool and other steels. This condition is just the opposite of carburization. Both processes depend upon the condition of the atmosphere surrounding the metal.

In addition to the removal of the carbon from the surface of steel, oxygen unites with many elements to form a class of compounds called oxides. The formation of the oxide of iron is illustrated in the iron and steel industry by the forming of a thick coating of scale on the surface of iron and steel parts when heated in an oxidizing atmosphere.

### *Iron Ore*

Iron, as we know it, is never found on the earth's surface in a free state, but is found in the form of a mineral known as iron ore, which is essentially iron oxide, containing anywhere from 50 to 70 per cent iron combined to a varying extent with the following impurities: oxygen, phosphorus, silicon, manganese, aluminum, lime, magnesium, and other elements that must be removed in the process of converting the ore into pig iron.

About four per cent of the earth's surface is made up of iron ore and man through scientific investigation has adapted such material to his use. This ore is usually found in depressions

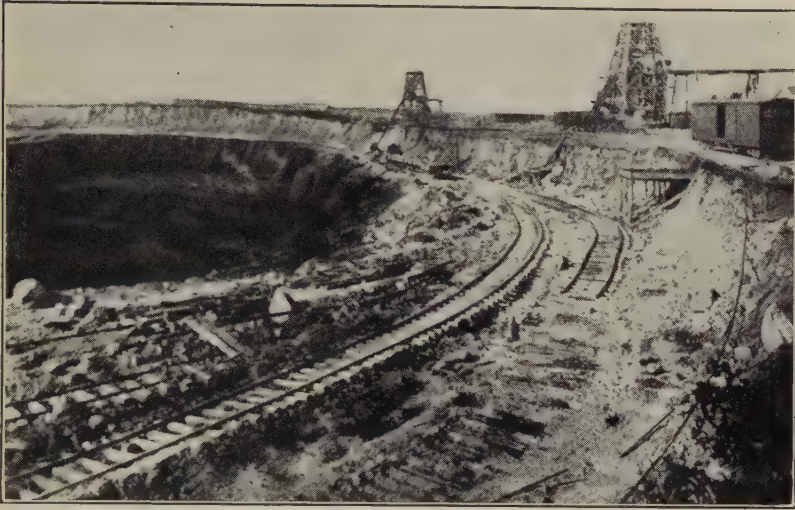


Fig. 4—An Iron Mine of the Open Pit Type.

in the earth's surface, most of these pockets being covered by glacial drift such as sand, gravel and boulders. The largest of these pockets is on the Mesabi range, a pocket of ore about four thousand feet wide and three hundred feet deep. (Fig. 3.)

Steam shovels strip off the glacial drift, sometimes reaching a depth of 50 or 60 feet. The iron ore is removed in like manner, Figs. 4 and 5, loaded on small flat cars, conveyed to the ore docks, and there loaded on the large ore boats. The modern ore boats of today are about 600 feet long by about 60 feet in beam, capable of carrying from ten to fourteen thousand tons of ore. With efficient mechanical devices for loading and unloading, a test showed that a boat could be loaded in sixteen and a half minutes, and unloaded in three and a half hours. Thirteen thousand tons of ore were removed. The enormous tonnage of this ore brought down the lakes totals in a single year from sixty to seventy millions of tons. Ore removed from the boat at one of the large steel mills is placed in piles for storage. (Fig. 6).

#### *The Blast Furnace*

The modern blast furnace of today is a tall circular structure ranging from fifty to one hundred feet in height, built of firebrick,



Fig. 5—Mining in an Open Pit Iron Mine.



Fig. 6—Ore Stock Piles Showing a Yard Crane and Three Blast Furnaces.

reinforced internally by a close-fitting steel shell, and incasing a circular space of varying diameter. (Fig. 7). On the bottom of this shell is located a number of tuyeres equally distributed around the upper circumference of the hearth. Their function is to provide passage for the blast of air that is provided under high pressure. What a difference in this furnace and the one described under the ancient method, the product of which was a small ball of iron. The modern blast furnace has a capacity of about 100 tons. These furnaces run twenty-four hours a day and three hundred and sixty-five days a year until shut down for repairs.

### *Pig Iron*

To produce pig iron, the following material is placed in the blast furnace: coke, iron ore, and limestone in definite proportions, depending upon the type of ore used. When this mass passes through the varying temperatures on its downward passage through the blast furnace, many chemical reactions take place until the iron ore has been transformed to molten pig iron.

To those desiring to study the chemical reaction of the metal Fig. 8 will be helpful.

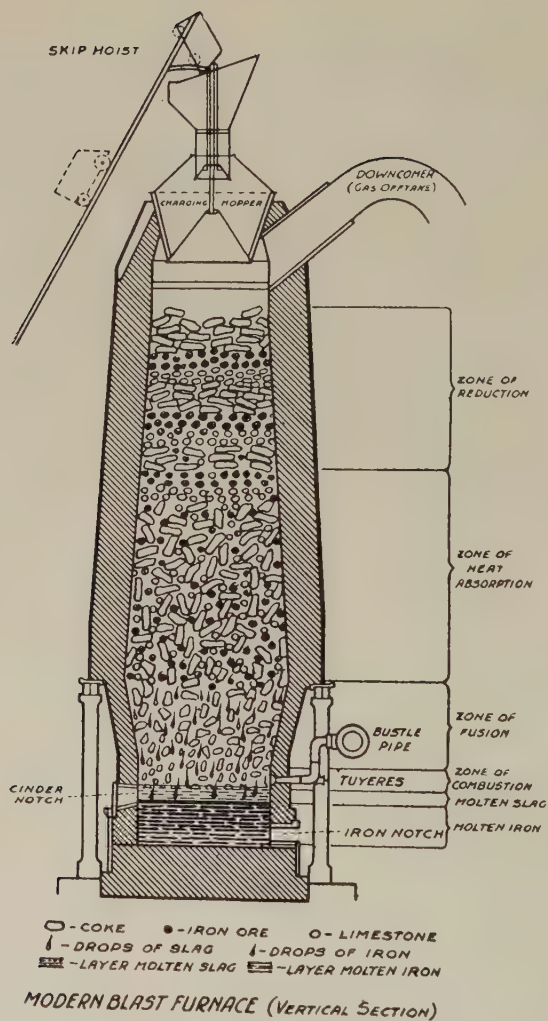


Fig. 7—Cross Section of a Blast Furnace.—Courtesy of Heat Treating and Forging.

Let us view the high spots of the chemical action. Coke is used in the blast furnace to generate heat and thereby melt the mass. The generation of heat is analogous to the combustion of your furnace fire on a cold morning when you increase the draft. The heated carbon of the coke (fuel) attracts the oxygen from the iron ore. The molten iron in turn attracts the carbon and other

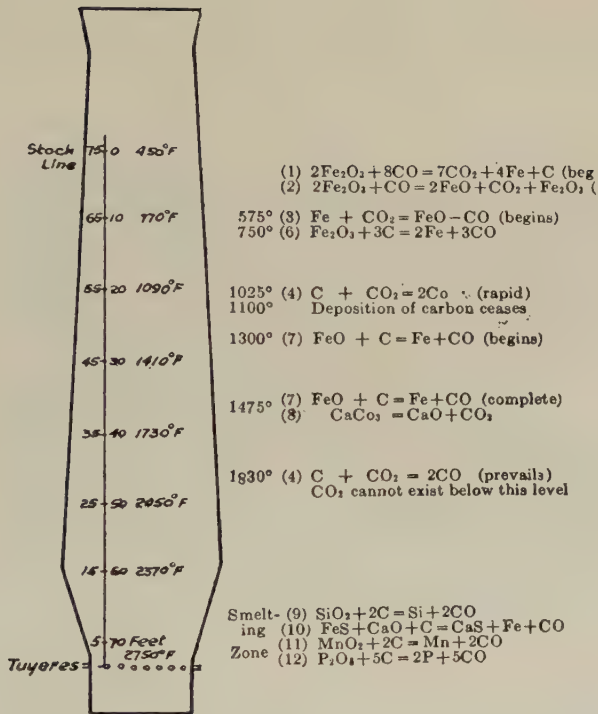


Fig. 8—Reaction Chart of a Blast Furnace.—Courtesy, Heat Treating and Forging.

impurities, phosphorus and sulphur, from the coke. The function of the limestone is to chemically unite with the impurities forming a slag which, being lighter than the molten iron, floats on top, analogous to oil on water. The slag is drawn off previous to tapping the iron. Molten pig iron will therefore contain the impurities it collects from the coke, less those impurities eliminated by the limestone in forming the slag. The impurities collected from the coke are carbon, some phosphorus and sulphur. The average chemical analysis of the product, pig iron, shows the following:

	Per Cent
Iron .....	91.00 to 94.00
Carbon .....	3.50 to 4.50
Manganese .....	0.50 to 2.50
Sulphur .....	0.018 to 0.100
Phosphorus .....	0.030 to 0.100
Silicon .....	0.25 to 3.50

By checking the analysis of iron ore in comparison with that of pig iron, it may be noted that the chief impurities picked up by the iron are carbon, sulphur and phosphorus.



Fig. 9—Sand Pig Bed.

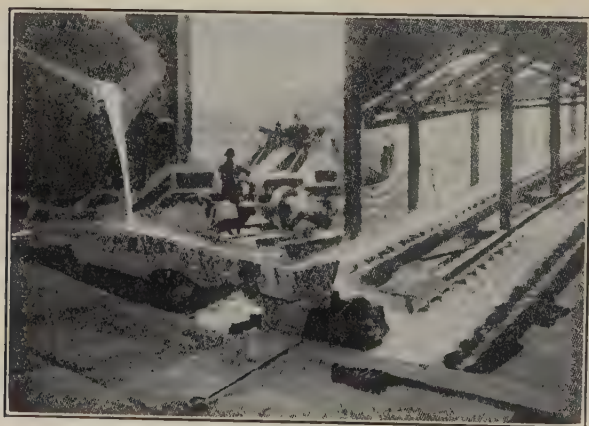


Fig. 10—A Casting Machine for Casting Pig Iron.

The pig iron was formerly poured into sand beds called pigs, Fig. 9. In the modern method the molten pig iron is poured into traveling molds on a conveyor system which passes the heated

mold containing the metal through water and dumps it into cars. This is known as a casting machine, Fig. 10. At this point, it is well to note that such material is the base of all of our commercial



Fig. 11—Sand Cast Pig Iron.

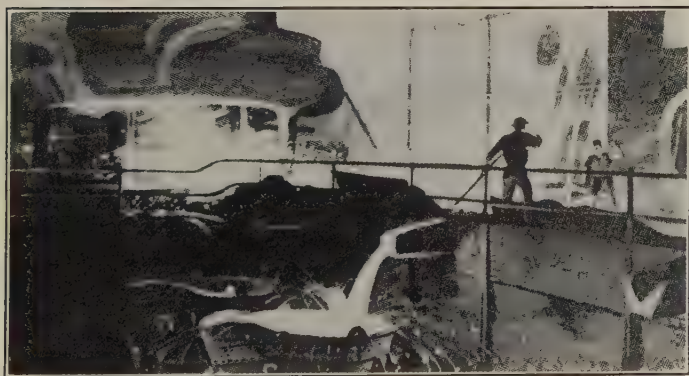


Fig. 12—Tapping a Blast Furnace Into a Receiving Ladle.

iron and steel. The process of manufacturing the different types or grades of steel consists in removing the impurities from the iron and adding further alloying elements which impart distinct characteristics to the iron. In the manufacture of cast iron, the pigs (Fig. 11) are charged into the cupola and the molten charge poured into molds. In the manufacture of malleable iron, the

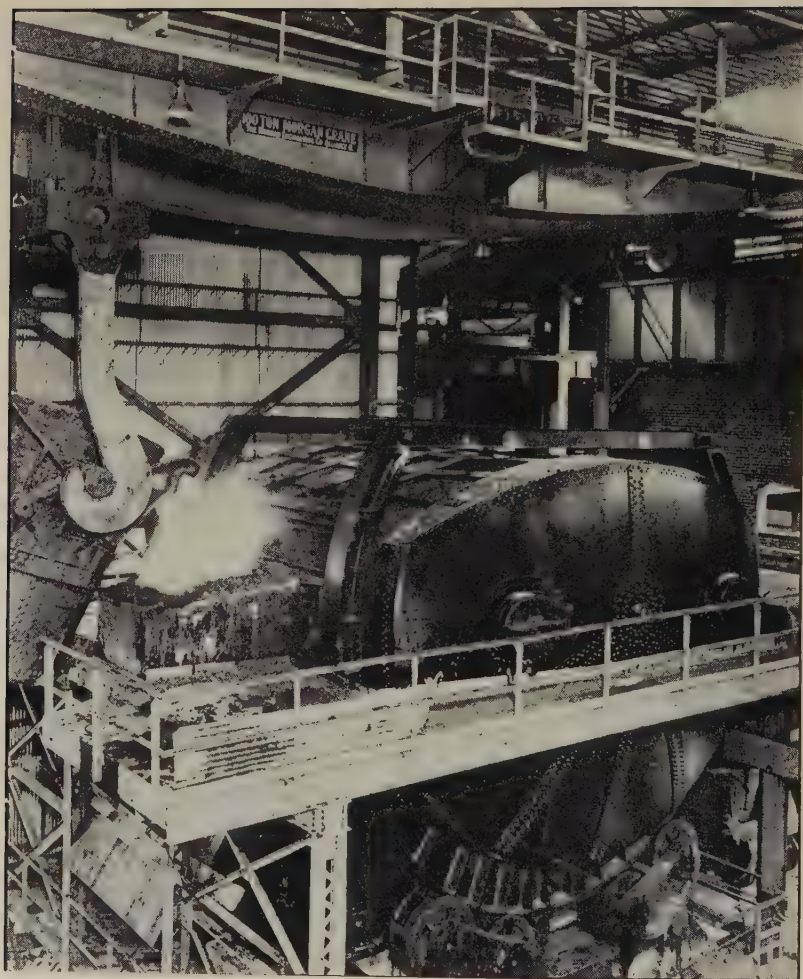


Fig. 13—A Hot Metal Mixer Being Charged with Molten Pig Iron.

product goes through a process of purification, is then poured into molds and thereafter graphitized by a process of annealing.

### *Manufacture of Steel*

Pig iron is the base of all of our modern steel. The various processes of manufacturing steel consist of removing the impurities more or less collected in the melting operation, and the addition of

numerous alloying elements that impart distinctive characteristics to the metal.

There are four general methods of manufacturing steel; the Bessemer, the open-hearth, the crucible, and the electric furnace processes. All four of these will be briefly described. At this stage, it would be well for those desiring to go into the details in any

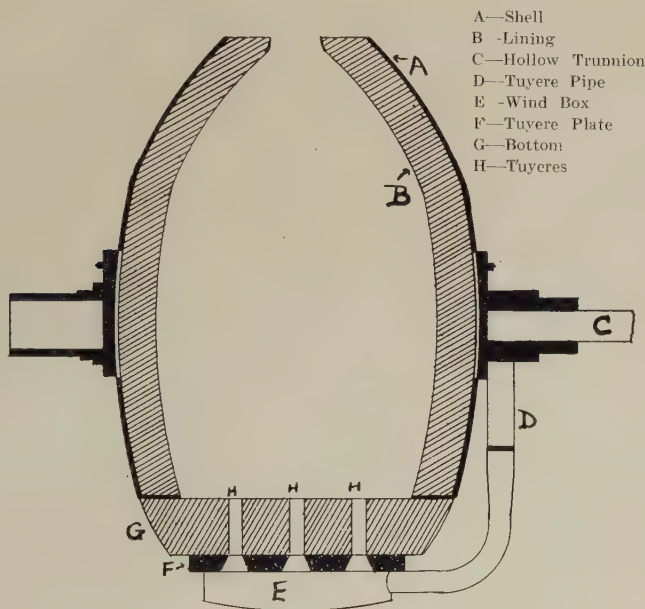


Fig. 14—A Cross Section Through a Bessemer Converter.

particular phase of this subject to procure a text book covering these points at length.

In the manufacture of steel by the Bessemer process the metal is usually tapped from the blast furnace into a ladle as indicated in Fig. 12 and transported to a "mixer" and stirred. A mixer is a large receptacle holding about 400 tons, for mixing and stirring metal tapped at various times from the blast furnace. The metal is usually poured in at the top as indicated in Fig. 13. The mixer rotates on trunnions or rolls, so that the metal can be withdrawn on the opposite side from that of pouring. Hot metal is transferred by ladle to either the Bessemer or the open-hearth.

*Bessemer Steel*

The Bessemer converter is a pear-shaped receptacle, hung on trunnions so that it can be tipped, Fig. 14. Air is forced through one of the hollow trunnions connected with a pipe which conveys the air to the air chamber at the bottom of the converter. In the bottom grate or tuyere plate are a number of holes through which cold air is blown under a heavy pressure and is passed up through the molten metal. To load the converter it is tipped forward into a horizontal position while 15 to 20 tons of molten metal are poured into it. The air is turned on while in that position. The converter is raised to a perpendicular position and the air passed up through the entire charge of molten pig iron. Curious as it may seem the temperature of the molten mass is raised to such a high point by the cold air blast that it is often necessary to inject steam or add scrap metal to lower the temperature. This increase in the temperature of the mass is due to the combustible elements, manganese, carbon and silicon, which will oxidize or burn. Even iron free from any of the alloying elements will burn readily if in contact with an excess of oxygen and particularly if the iron be molten. When we consider that the molten metal is combustible when in contact with oxygen it may be analogous to a house heating furnace when the draft is opened. The combustible elements in the fuel burn and increase the temperature until all of the combustible elements are oxidized or burned out, the volatile matter first and then the carbon. In the converter the rise in temperature is caused by combustion of oxygen and carbon, manganese and silicon contained in the molten iron. These elements are reduced to a very low percentage.

When the air is forced through the molten metal we first see small sparks consisting of iron and slag issuing from the mouth of the converter. In about two or three minutes a small tongue of reddish-yellow flame appears, evidence of the silicon oxidizing. The flame changes to a greenish tint, evidence of the manganese beginning to oxidize. The flame increases in size and brilliancy until a white hot flame some 25 to 30 feet in height shoots from the vessel with a loud roar, Fig. 15. This is caused by the oxidizing or burning of the carbon. The appearance of these operations is similar to a beautiful display of fireworks. This "boil" con-



Fig. 15—Bessemer Converter During the Blow.

tinues until the end of the operation. When the flame diminishes and begins to flicker or “feather” at the edges, it is a warning that the carbon is nearly all oxidized. Finally the flame shortens or drops, evidence of the carbon being all burned out or, at least, very low in percentage.

A Bessemer converter melter must be capable of judging by

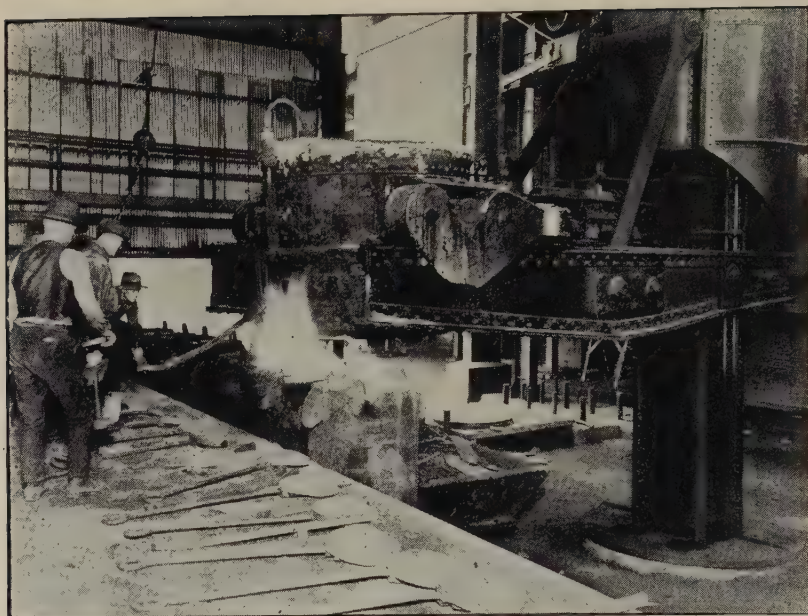


Fig. 16—Pouring Ingot Molds.

the height, color and end-point of the flame, the point at which the air is shut off. Attempts have been made to apply the spectroscope to this work, but without success. The eye alone is depended upon. The melter aims to blow down to some definite point at which the carbon is practically eliminated, and then to recarburize to the desired content by the addition of coal or coke. Great care must be exercised for if the blast be continued too long, it will burn up the iron. Carbon, manganese and silicon previously melted in a cupola are added to the mass, usually in the receiving ladle.

Manganese is added to reduce the sulphur and oxygen which the metal has absorbed. If too large a percentage of the sulphur is present it will make the metal "hot short", causing it to roll or forge only with difficulty, at a red heat. In this process the phosphorus which goes into the furnace in the ore and coke is not reduced, but remains in the finished steel. An excess of phosphorus would cause the metal to become "cold short", the steel being brittle in the cold state.



Fig. 17—Charging Side of an Open-Hearth Furnace.—*Courtesy of Bethlehem Steel Co.*

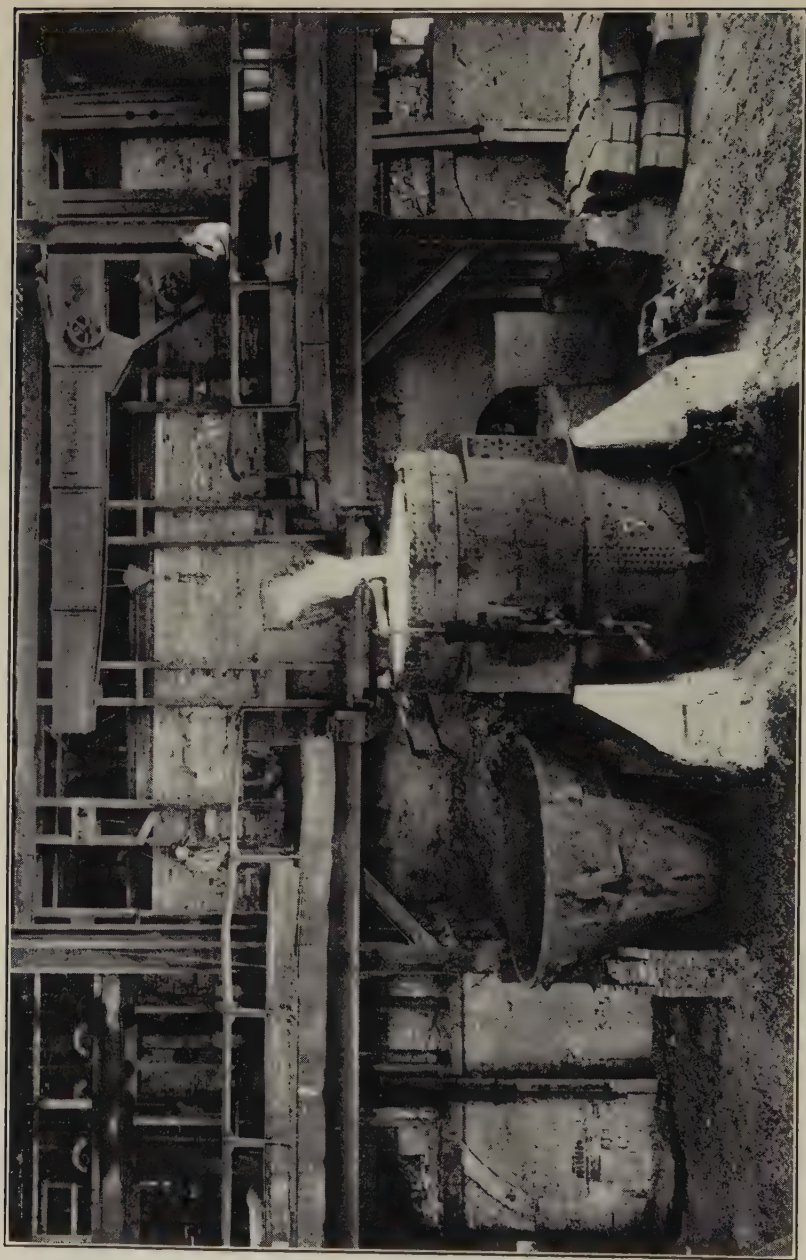


Fig. 18—Pouring Side of an Open-Hearth Furnace.—Courtesy of Bethlehem Steel Co.

When in the opinion of the melter it is time for the blow to be shut off the metal is poured from the converter into a large ladle and allowed to stand for a period of time to allow the boil to be completed and the slag to separate. If the steel is to be used for commercial stock, the metal is poured directly from the ladle into ingot molds, Fig. 16, and finally rolled into commercial shapes. This product is known as Bessemer steel, and is used chiefly for structural shapes, plates, screw stock, etc. The process is the quickest known method of partially purifying pig iron, 15 tons requiring about 15 to 20 minutes. Bessemer steel is fairly low priced. If a higher degree of refinement is necessary and the product is to be used for fatigue resisting material or tools, the molten metal from the converter is transferred to the open-hearth furnace for further purification.

### *Open-Hearth Process*

The open-hearth process of making steel employs the open-hearth furnace in which the molten or cold pig iron, cold scrap iron and steel are placed. This mass is melted by gas or oil, and a proportioned amount of air. Fig. 17 shows the charging side of an open-hearth furnace, and Fig. 18 the pouring side.

When the charge is molten, a certain amount of iron ore, iron scale, or some other oxidizing material is put into the melt. The chemical reaction of this material keeps the mass in agitation, thus oxidizing and lowering the excess carbon and phosphorus until the proper percentage is acquired. The melter makes this determination in the following manner: He observes the condition of the molten mass and at intervals dips out a spoon-ladle full of metal and pours it into a test mold. As soon as this test is solidified, it is cooled in water, broken, and from the appearance of the fracture, the melter can usually estimate the percentage of carbon, within 0.02 or 0.03 per cent. A slight variation in the percentage of carbon will show a different fracture noticeable to the trained eye. The importance of the melter or mill expert, and the training required to perform this task can best be imagined when we consider that the quality of the 100 tons of metal depends entirely upon his judgment and decision as to when the furnace shall be tapped. In procedure controlled mills a quick laboratory analysis

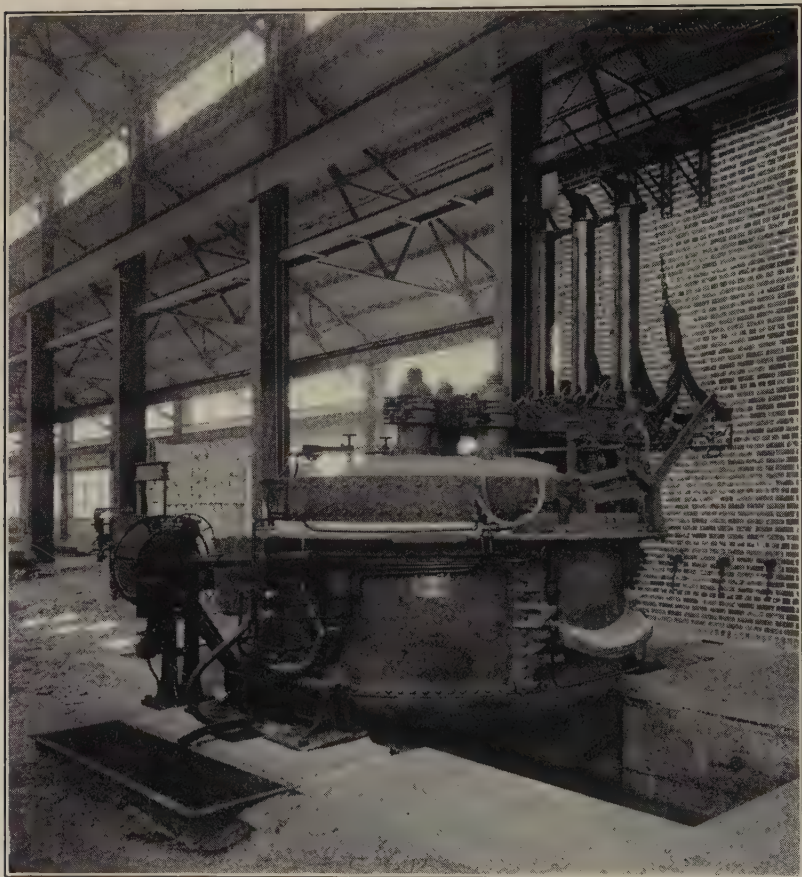


Fig. 19—An Electric Furnace.

is made for the important elements which takes about 20 to 25 minutes. It is used to check the melter's observation.

Before tapping, the required percentage of manganese is placed in the ladle. The molten steel is then poured by means of a ladle into ingot molds. A small test mold for final laboratory analysis of that particular heat is numbered. The ingots are placed into a soaking pit, reheated and rolled or hammered into shapes for commercial use.

More than 80 per cent of the carbon and alloy steels are made by this process and we can safely say that the percentage is on the

increase due chiefly to the highly efficient metallurgical control throughout the entire process of manufacture.

### *Electric Furnace Process*

Due to this fact and to the excessively rigid requirements of a high grade steel in this day of high speed, power and production, a small percentage of the product is further refined in the electric furnace. The impurities phosphorus and sulphur are the bane of engineers, designers and all users of steel. The electric furnace facilitates the elimination of phosphorus the same as in the open-hearth furnace, by the combined action of lime and oxide of iron. Desulphurization can be carried much further in the electric furnace than in a Bessemer furnace, or open-hearth furnace on account of the ease with which slagging operations can be controlled. Fig. 19 shows a typical installation.

There are two branches either of which may employ basic or acid slags; first, the cold scrap process; the second, the hot metal process. The use of basic slags will be briefly described. In the cold scrap process 1 to 10 tons of steel scrap are melted under an oxidizing slag which removes practically all of the silicon, most of the manganese, part of the carbon and nearly all of the phosphorus in the scrap. This oxidizing slag is removed by hand rabbling and the metal recarburized if desired. A reducing slag is then used to deoxidize the metal and remove sulphur, of which 70 to 90 per cent is removed. The ferro-alloys necessary for the grade of steel to be made may be added to the metal in the furnace. After the bath is deoxidized and all the necessary alloys are dissolved and uniformly distributed, the temperature is adjusted and the heat tapped.

In the hot metal process the melting and oxidizing is carried out in another furnace, usually an open hearth, and after the silicon, manganese, carbon and phosphorus are removed to the point desired, part of the molten metal is transferred to an electric furnace where it is deoxidized and desulphurized by means of a reducing slag. The hot metal process is used for the manufacture of electric steel in large units, from 10 to 50 tons. It produces this large tonnage with a minimum of power consumption.

With the acid slag, operation is quite similar, except that only one slag is used. Manganese, silicon and carbon are oxidized by

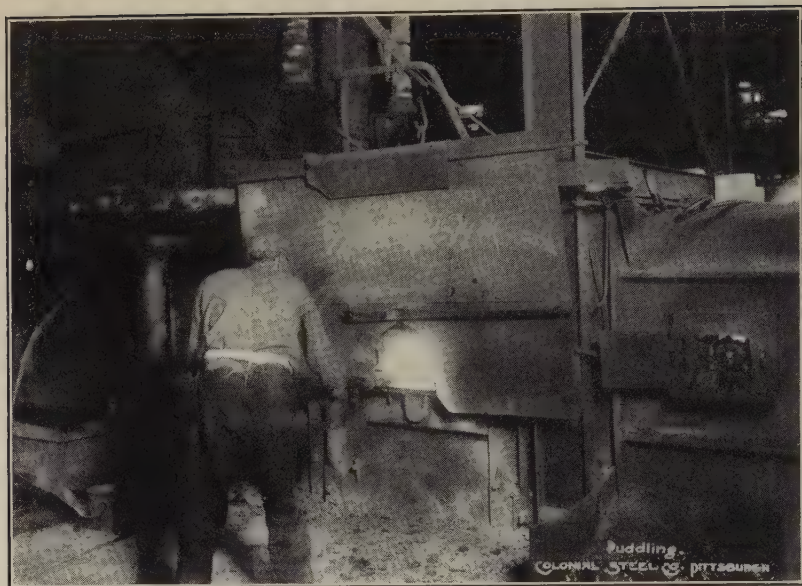


Fig. 20—Front View of a Puddle Furnace.—*Courtesy of Colonial Steel Co.*

using mill scale. The excess oxides are worked out of the bath, and the heat is tapped. Phosphorus and sulphur are not appreciably lowered by the acid slag.

The electric process is a comparatively recent introduction into the iron and steel industry. It has the great advantage over the Bessemer and open-hearth processes in that positive deoxidation may be accomplished in the furnace instead of in the ladle and that the reaction products from the recarburizers and deoxidizers have plenty of time allowed for them to leave the metal and join the slag. The product of the electric process may, therefore, be made much more sound and free from oxidation defects than the product of the Bessemer, or acid or basic open-hearth, all of which are more or less oxidizing up to the moment of tapping. In addition, the basic electric process is the only steel-making process that will remove sulphur to very low percentages. The electric process has a great advantage over the crucible process in that steel of just as high quality may be made in lots of several tons instead of the 100 and 150 pound lots made in the crucible process.

A large per cent of our present high grade alloy, tool, and

high speed steels are made by this process. However, in all processes, oxidation causes some of our troubles.

### *The Puddling Process*

This process reduces the impurities and decarburizes the metal. In the manufacture of wrought iron the puddling furnace is charged with either cold or molten pig iron. The iron is stirred up with a large iron bar called a "rabble bar," and kept boiling until the carbon is nearly all burned out. The other impurities separate from the iron and form the slag or puddle cinder. See Fig. 20.

The purer the iron, the higher is its melting point. Pig iron melts at about 2150 degrees Fahr., steel at about 2500 degrees Fahr., and wrought iron free from carbon, at about 2750 degrees Fahr. The temperature in the puddling furnace is maintained above the melting point of pig iron, but not high enough to keep wrought iron in a liquid state. The purification of the metal is assisted by the constant stirring or "rabbling" of the molten mass by the "puddler." The principle of this process is exposing the metal thoroughly to the oxidizing influence of the air. As soon as the small particles become purified, they partly congeal and drop to the bottom, forming a pasty mass. The puddler separates this mass into "balls." In this operation a small per cent of the slag is trapped or mixed with the iron. After the balls have been formed, they are removed to the hottest part of the furnace for a final welding heat before they are removed to the "squeezer." Fig. 21 shows a ball of iron being removed from the furnace. The ball is elongated vertically. Welding takes place and some of the slag is expelled through an open space between the rolls as in Fig. 22. The metal is then passed through rolls to be formed into bars called "muck" bars. In this state it is of no commercial value as bar stock except for use as a base in the manufacture of steel. This material when further welded and worked is also the base for much of our high grade stay bolts, chains and parts that require a soft, ductile and weldable iron. To produce iron for these purposes the muck bars are piled, heated to a welding heat, and hammered or rolled into commercial bars. For a higher grade material they are again welded and rolled into smaller bars and then box-piled, welded and again rolled into the finished size for high grade chain and other service material. In each of these operations the



Fig. 21—Removing a Ball of Puddled Iron from the Furnace, Prior to the Squeezing Operation.—*Courtesy of Colonial Steel Co.*



Fig. 22—A Squeezer Used for Rolling Muck Bar.—*Courtesy of Colonial Steel Co.*

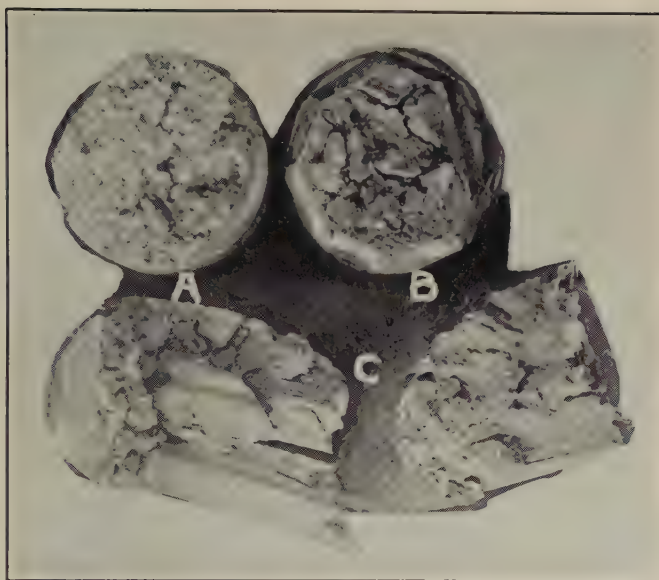


Fig. 23—Wrought Iron Fractured, Showing the Long Fibrous Structure.



Fig. 24—Shearing Muck Bar.—*Courtesy of Colonial Steel Co.*

object is to more minutely unite it by welding the pasty particles, to remove excess slag and to elongate the remainder into so-called fine fibers. This type of wrought iron has an approximate tensile strength of 40,000 pounds per square inch and 40 per cent elongation. Fig. 23 is a photograph of three distinct fractures which will better illustrate the points. The fracture A shows the true crystalline structure. The fractures B and C show the long fibers of a longitudinal fracture.

### *Crucible Process*

The next method to be described is the crucible process. It was one of the first methods for producing high grade steels and is in use to considerable extent today. Crucible steel derives its name, as do the Bessemer and open-hearth steels, from the process by which it is made. This steel, instead of being made from the pig iron, like the other steels, has for its base muck bar or wrought iron, which was produced by the puddling process.

Bars of the desired analysis are sheared into small pieces as indicated in Fig. 24 to form the crucible charge. The charge is placed in the crucible which holds about 90 to 100 pounds, Fig. 25, and is covered with a lid to prevent the products of combustion from contaminating the metal. The crucibles are then placed in the furnace, which may hold as many as 36 crucibles Fig. 26. The melting takes on an average of three to four hours. Examination of the charge is made by removing the cover to make sure it is entirely melted, after which it is kept in the furnace a sufficient length of time in order that it may turn "dead," so that it will pour quietly without the evolution of gas. If poured before it is "dead" the ingots will contain some gas. If the "killing" time is too long, the ingots will be solid but the steel will be hard, brittle and weak. The crucible process is almost entirely a melting process. Practically no alloys are lost or reduced in melting.

### *Summary of Steel Making*

The following table shows the steel production in the United States according to the census for the year 1925. The figures are given in long tons (2,240 pounds per ton).



Fig. 25—Packing the Charge in Crucibles.—*Courtesy of Colonial Steel Co.*



Fig. 26—Drawing Crucibles from a Crucible Furnace.—*Courtesy of Colonial Steel Co.*

Table I

Method of Steel Production	Tons	Per cent of Total Ingots Produced
Total ingots produced.....	45,119,000	100.0
Open-hearth .....	37,909,000	84.0
Basic open-hearth .....	37,055,000	82.0
Acid open-hearth .....	854,000	1.9
Bessemer converter .....	6,701,000	14.5
Electric furnace .....	448,000	1.0
Crucible furnace .....	19,000	0.4

It is interesting to note that the tonnage of crucible steel produced in 1925 is approximately one-third of that produced in 1919. The tonnage of electric steel produced in 1925 is nearly double that of 1919.

### CARBON

Of all the alloying elements that enter into the manufacture of steel, carbon is the most important. Its strong chemical affinity for iron and its dominating influence on physical properties gives it prominence in any problem relating to steel. Although of itself carbon as such does not possess strength or hardness, except in the diamond form, it adds both of these properties to iron. All iron contains at least a trace of carbon. It further decreases ductility and malleability, and lowers the magnetism and electrical conductivity of steel. The percentage of carbon is always a factor to be reckoned with. As the percentage of alloying elements is increased or decreased, the influence of carbon is varied considerably.

The element carbon occurs free in nature in the crystalline form as diamond and graphite, and in the amorphous form as coal. It is one of the chief constituents of the bodies of plants and animals. It is a part of all natural fuel and of nearly all prepared fuel, and occurs in a combined state in limestone, magnesite, marble and other carbonaceous rock.

It may be well to keep the following points in mind for further study of the subject. Carbon is "allotropic" and is found in three states, the diamond, amorphous carbon and graphitic carbon. (While the following statement is not theoretically correct, it may help the student to a better interpretation of the subject.) Carbon likewise may be found in all three states in iron; as the diamond,

in hardened steel; as amorphous carbon in annealed steel; and graphite in cast iron.

In pig iron, carbon occurs in two forms, graphitic carbon and combined carbon. Graphitic carbon, practically pure carbon, exists in pig iron in the form of tiny flakes which are distributed throughout the mass. In pig iron it forms during the process of cooling. Graphitic carbon gives to pig iron the grayish-black appearance. See Fig. 27. In the cooling, some of the carbon con-

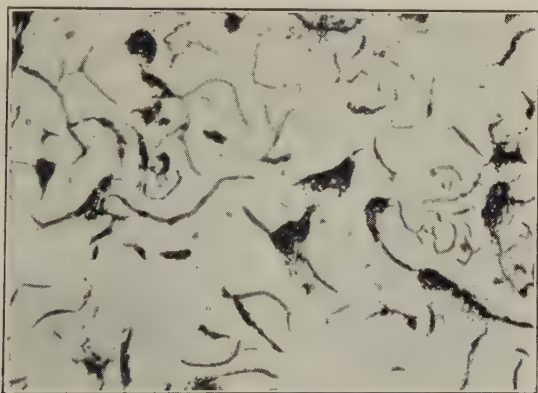


Fig. 27—Photomicrograph of Cast Iron Showing Graphite.

tinues in combination with the iron as a definite chemical compound, iron carbide ( $\text{Fe}_3\text{C}$ ) which contains 93.33 per cent iron and 6.67 per cent carbon. Both forms of carbon produce marked effects upon the properties of the iron. The tendency of the graphitic carbon is to weaken, while the combined carbon up to the limit of about 0.90 per cent strengthens the iron.

In metallography, the compound iron carbide is called "cementite," and to the free iron is given the term "ferrite." In cooling, these two substances conduct themselves in a peculiar way toward each other. In passing a certain temperature (about 1290 degrees Fahr.) they arrange themselves in layers in the definite amounts of approximately seven parts ferrite to one part cementite. The resultant stratified aggregate will contain approximately 0.90 per cent carbon. Under the microscope these stratifications present the appearance of mother-of-pearl and have been named "pearlite," Fig. 28. Pearlite is the strongest constituent of cast iron. When heated, iron absorbs carbon and above the fusion point this ab-

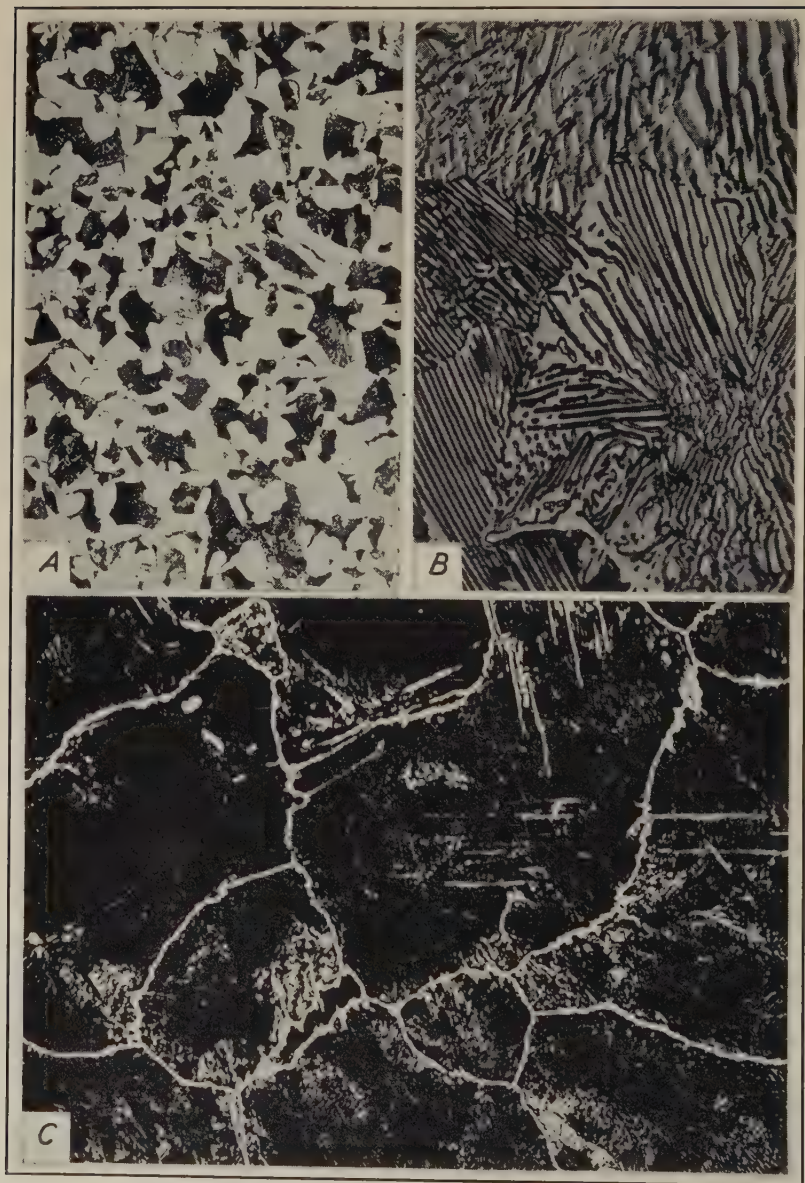


Fig. 28—28a. Photomicrograph of a Forging Containing 0.85 Per Cent Carbon. Black Areas are Pearlite Grains, White Areas are Ferrite Grains.  $\times 100$ .  
 28b. Photomicrograph of a Pearlite Grain at High Magnification,  $\times 1000$ , Showing the Plates of Cementite (Dark Plates) and Ferrite (Light Plates).  
 28c. Photomicrograph of Steel Containing 1.25 Per Cent Carbon. The White Net Work is Cementite Thrown Out of Solution by Slow Cooling to the  $A_{r3-2-1}$  Critical Temperature.  $\times 125$ .

sorption becomes very rapid. The limit, called the saturation point, beyond which it will not absorb any carbon, varies with the temperature.

The amount of free carbon or graphite is affected by the amount of silicon present, a high percentage of silicon causing a corresponding decline in the amount of combined carbon. Silicon tends to decrease the combined carbon and increase the graphitic carbon. Manganese and chromium have the opposite effect. Rapid cooling tends to prevent the formation of graphite. In general, the more rapid the cooling, the less the graphitic carbon and the greater the combined carbon.

From these statements, you will probably begin to realize that carbon plays a very important part in the manufacture of steel.

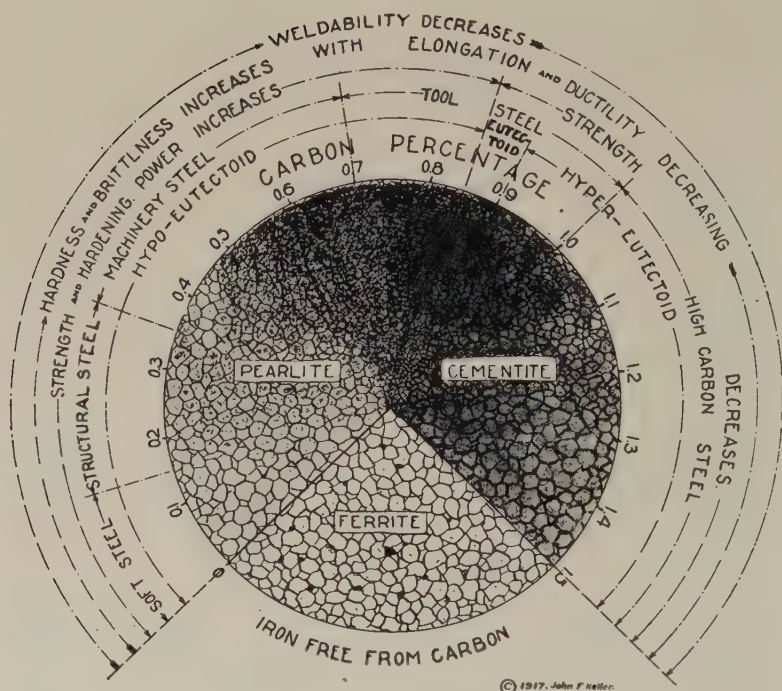
To further emphasize and perhaps more clearly picture the effects of carbon when combined with iron in definite proportions, the following table has been selected from Sauveur's "Metallography of Iron and Steel."

**Table I<sup>2</sup>**  
**Strength of the Micro-Constituents of Steel**

Constituent	Strength lbs. per sq. in.	Elongation in 2 inches	Hardness	Hardening Power
Ferrite . . . .	40,000 lbs.	40%	Soft	None
Pearlite . . .	125,000 lbs.	10%	Hard	Maximum
Cementite ..	5,000 lbs.	0%	Very hard	None

A careful study of this table shows that the presence of carbon in iron affects the hardness and strength of the resultant steel, depending upon the percentage of carbon combined with the iron. It will also affect the position of the critical temperature, explained in a later chapter. To obtain a clearer picture of this table, a pen sketch is included and is the author's conception of that table, indicated in Fig. 29.

Referring to the table, it will be noted that the constituent ferrite (wrought iron) has a tensile strength of about 40,000 pounds per square inch. That is, a piece of wrought iron one inch square will sustain a load of 40,000 pounds, but if a greater load is applied it will stretch, because it is ductile and is capable of elongating about 40 per cent before failure occurs. In addition,



CONSTITUENTS	STRENGTH	ELONGATION	HARDNESS	HARDENING POWER
Ferrite	40,000 lbs.	40 %	Soft.	None.
Pearlite	125,000 lbs.	10 %	Hard.	Maximum.
Cementite	5,000 lbs. ?	0 %	Very Hard.	None.

Fig. 29—Diagrammatic Representation of the Structure of Iron Containing Varying Percentages of Carbon.

the metal will reduce in cross section (reduction in area) before failure occurs. These characteristics are the chief reasons for such metal being used for chains, bolts, and other parts of machinery where the stretching is an indication or a warning that the metal has been over-loaded. Under the heading "hardness," it may be noted that this metal is indicated as soft, meaning that the metal can be worked hot or cold. This is possible owing to its ductility. Under the term "hardening power," it will be observed that such metal has "none," signifying that such iron will not harden. To demonstrate, if a piece of wrought iron is heated to a bright red

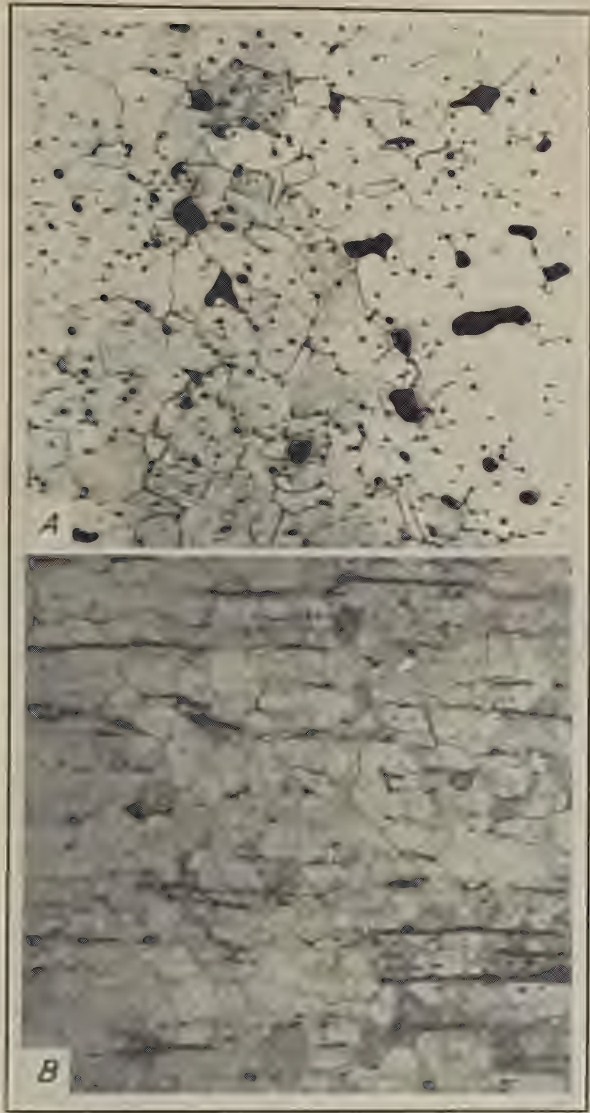


Fig. 30—30a. Photomicrograph of Cross Section of a Wrought Iron Bar. The Black Spots are Slag Inclusions.

30b. Photomicrograph of Longitudinal Section of a Wrought Iron Bar. The Black Stringers are Slag Inclusions Elongated by Rolling. The Grains are Ferrite.

heat and quickly cooled in water, there will be no appreciable hardness unless such metal, during the process of heating, came

in direct contact with carbonaceous fuel. If the surface should become hard, this would be evidence of surface carburizing, as previously explained.

Wrought iron is usually classed as "fibrous." This is true only when the metal is stretched in the process of rupture, and therefore, appears "fibrous" because the soft ductile grains of ferrite have been elongated during manufacture and also to the fact that wrought iron usually contains about 2 per cent of trapped slag, as a result of its method of manufacture. If a piece of such unstretched metal be cut in any direction, polished, properly etched and examined microscopically it would show a crystalline structure with spots of slag in the cross section and the slag elongated in the longitudinal section since the slag was elongated or drawn out in the rolling process. In Fig. 29, the crystalline structure and slag are indicated in the sector marked "ferrite" and also in Fig. 30, which shows sections of a wrought iron bar.

The soft and ductile characteristics of wrought iron (ferrite) should be kept in mind because it is this general type of metal that usually forms the base of all of our high grade alloy and tool steel. However, these characteristics may be changed and others added by the use of varying alloy elements, for instance, a small percentage of carbon combined with such iron imparts two distinct characteristics, strength and hardening power.

When carbon is added to molten iron the carbon and iron form a liquid solution. When such metal is allowed to cool slowly to atmospheric temperature, the carbon will precipitate out of solution as the definite chemical compound  $\text{Fe}_3\text{C}$ , forming a eutoid already referred to and known as "pearlite." This is indicated in the left hand sector of Fig. 29 by the small black areas in low carbon steel which increase in number until the iron is saturated at the "eutectoid" composition marked 0.90 per cent carbon. This constituent has been given the name "pearlite" because when such a metal is properly prepared and examined under a high powered microscope it looks like "mother-of-pearl." Again by referring to Table II it may be noted that ferrite has a strength of 40,000 pounds per square inch. By the addition of a small amount of carbon, 0.90 per cent in the form of charcoal, coke or other carbonaceous material, we note that the strength of the iron in the form of "pearlite" has been increased to 125,000 pounds per square

inch. Under the heading "elongation" we find that it has been reduced to 10 per cent, indicating that the previously soft ductile metal has now become brittle. A simple experiment will demonstrate this point. Take ordinary chewing gum, as representing soft ductile iron, mix with it a small quantity of sand, pull it and note the results. As the quantity of sand increases the gum finally becomes exceptionally brittle, accompanied by a very slight elongation or stretch, similar to cast iron.

Under the term "hardness," we note that the metal is hard, that is, the hardness of the steel would be in proportion to the percentage of carbon present and combined with the iron up to the eutectoid composition, 0.90 per cent. Therefore, such steel must be annealed for machining purposes. Under "hardening power," we note there is a maximum hardness. This is true only if the steel contains the eutectoid composition, 0.90 per cent carbon. If such a piece of steel were heated uniformly throughout the mass to just above its "critical temperature" and cooled quickly, it would develop the maximum hardening power in that steel. On slow cooling steel containing more than 0.90 per cent carbon through the critical range to atmospheric temperature, the excess carbon above 0.90 per cent is thrown out of solution in the form of free "cementite" indicated on the right hand sector of Fig. 29 marked "cementite." This constituent derives its name from the cementation process previously described. In this state steel may be likened to a concrete wall made up of a stone aggregate and having a strength analogous to the strength of pearlite. The stone is held together with a brittle cement. This mechanical mixture would be efficient in compression but would be undesirable in tension members. See Fig. 28c.

By referring to Table II under the constituent cementite, we note that this material has a strength of only 5,000 pounds per square inch. Cementite has no elongation, and is therefore a very brittle substance. Cementite is very hard and requires a special annealing process to make it machinable.

### *Pouring the Ingot*

Steel made by any of the various processes and intended to be fabricated into commercial shapes or bars is poured into molds,



Fig. 31—Pouring Ingots from an Open-Hearth or Converter Heat. Courtesy of Bethlehem Steel Company.

called "ingot molds," Fig. 31. Great care must be exercised in this operation, otherwise many defects are created which may exist in the finished product. As previously stated, we have not yet reached the ideal in the manufacture of steel.

The principal defects are piping, blow holes, cold shuts, segregation, ingotism, scabs, checking and slag inclusions. It would

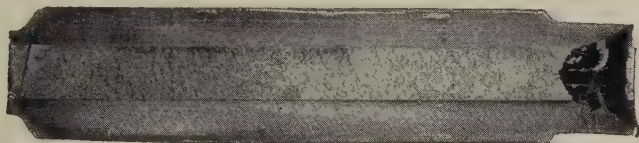


Fig. 32—Cross Section of an Ingot Showing the Pipe or Shrink.

be well to remember pouring steel into an ingot mold is similar to pouring a casting. The ingot inherits most of the characteristic defects found in a casting. The shrinkage cavities due to the contraction of the liquid iron or steel are inherited in the ingot mold in the form of a shrink portion or "pipe," Fig. 32. This portion, usually exposed to the air, becomes oxidized by the formation of a thick coating of scale which usually prevents welding of the pipe even in weldable steels. Blow holes are due to the gases in steel which try to escape through the partially congealed mass. Owing to the solidification of adjacent metal the gases cannot escape and so form gas cavities known as "blow holes." If these occur close to the edge of the ingot their surfaces are likely to become oxidized and therefore weld with great difficulty, even in weldable steel. If not welded, such cavities cause seams in the finished metal. The impurities carbon, manganese, phosphorus and sulphur form compounds with iron, having a lower freezing point than that of iron and remain liquid for a greater length of time. They segregate out of the iron during its solidification. Scabs may be caused by splashing of the molten metal against the cold mold. These are removed by chipping in the higher grades of steel but are not removed by chipping in the lower carbon steels because such ingots are usually clogged down at a welding heat. Checking is usually caused by rough or cracked mold surfaces which prevent normal contraction of the ingot at its surface.



Fig. 1.—Stripping Ingot Molds from Solidified Ingots. Courtesy of Bethlehem Steel Co.

### Sonims

Nonmetallic inclusions, better known as "dirt," in steel are technically known as "sonims." They are usually particles of slag, alumina or manganese sulphide. In addition, there are other defects that may be created in the cooling, fabrication and annealing which will be touched upon later. Through scientific investigation and the education of the personnel controlling these operations most of these defects are reduced to a minimum. The rigid requirements of material for high power transmission demand clean steel.

Let us summarize the conditions governing welding of internal defects during forging and rolling. (1) It is impossible to unite two plates of iron or steel by welding unless the coating of iron oxide or other impurities is removed from between the plates. (2) The temperature necessary to melt and remove such oxide is very close to the melting point of high carbon steel. (3) High carbon tool steel is very seldom, if ever, heated or rolled at a welding heat owing to the danger of burning and disintegration when hammered or rolled, but low carbon steel is rolled at a welding heat. (4) High speed or hard alloy steels are unweldable. Therefore, there are only three methods of eliminating these defects: (I) prevention of their formation in the ingot, (II) welding where possible and (III) removal by chipping, etc.

### Crystallization of Steel Ingots

When the metal is solid in the ingot mold, the ingot is stripped

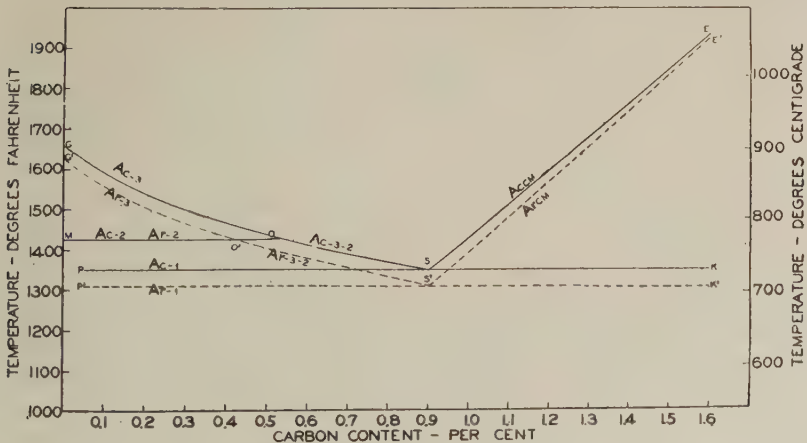


Fig. 34—Constitution Diagram of the Iron-Carbon System.

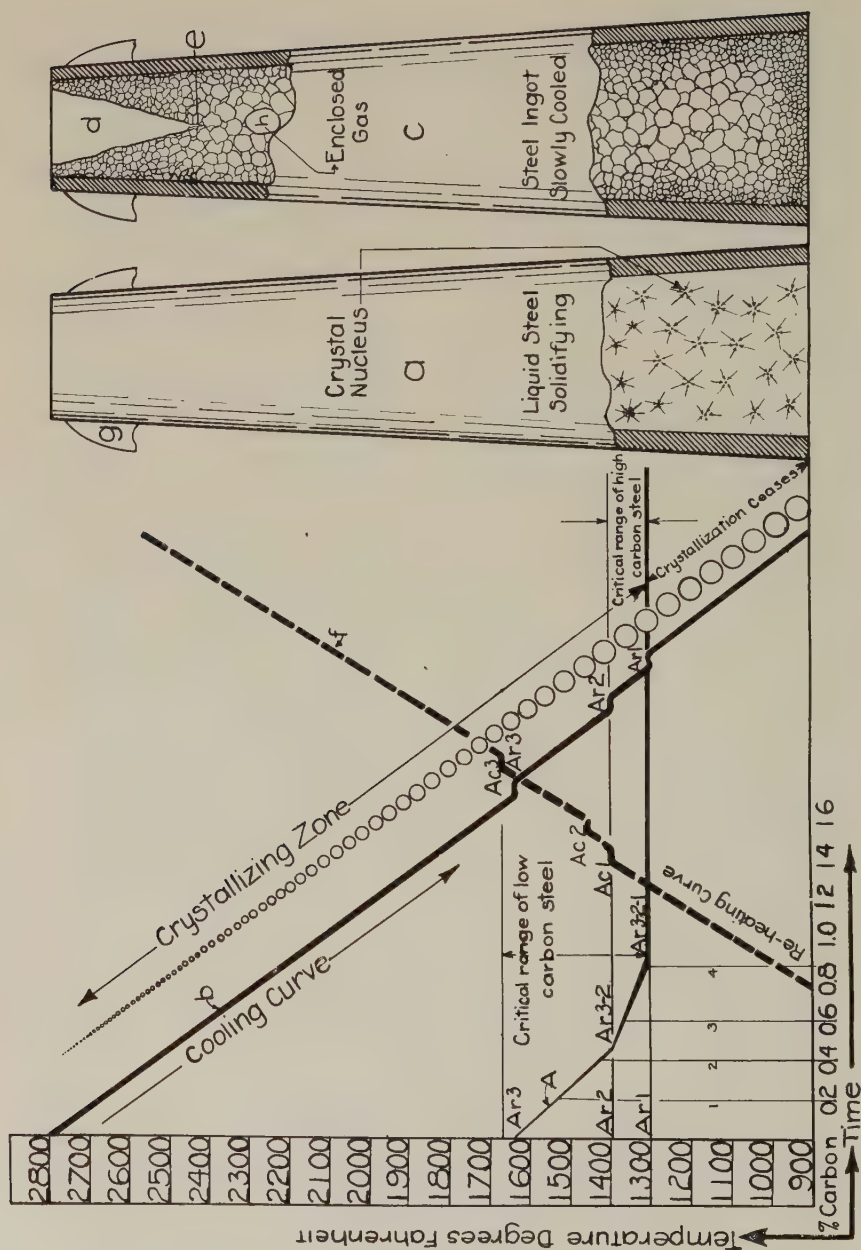


Fig. 35—A Presentation of the Crystallization of a Slowly Cooled Ingot.

of the ingot mold, Fig. 33. During the cooling period the molten metal in the ingot freezes or crystallizes until it is all solid. In passing from the temperature of solidification down to room temperature several structural changes take place. Fig. 34 shows these changes diagrammatically and is known as a "constitution diagram." Temperatures are read in a vertical direction and the amount of carbon present in per cent is read in the horizontal direction. The black lines show the "critical points" on heating and the dotted lines show the critical points on cooling. A portion of this constitution diagram is shown in the left hand lower corner of Fig. 35. We will refer to these critical points in discussing the cooling of metal in an ingot. They will be elaborated on in a later chapter.

The development of crystals as the metal cools from the liquid state, depends upon two factors: First, the length of time required for the ingot to cool to the lowest point in the critical range, indicated by the line  $Ar_{3-2-1}$ ; and second, the impurities in the metal, particularly phosphorus or sulphur, both of which seem to aid grain or crystal growth. Most other alloying elements such as manganese, molybdenum, chromium and vanadium tend to retard the rate of grain growth. Fig. 35 is a diagrammatic representation of the formation of the crystalline structure in an ingot of steel.

Crystal nuclei at "a" are represented by small dots. These nuclei attract surrounding crystal matter. This attraction is influenced by alloying elements and the length of time the metal retains heat above the lowest point of the critical range, indicated by the line of circles parallel to the cooling curve "b." The circles also represent the relative size of the crystals or grains. The longer the metal remains in the crystallization zone above the lowest point of the critical range, the greater the grain development. Growth is proportional to time and depends upon the alloys present and "c" represents a solidified ingot. The metal close to the mold solidifies and cools first, while the center of the ingot requires a longer time to cool. Therefore, the position of the crystals is not prevented by the rigidity of the metal. The pipe end of the ingot, marked "d" is defective and should be cut off along line "e". Failure to do so will cause a serious defect usually a seam in that portion of the finished product. Blow holes or gas pockets near the edges will cause seams, especially in unweldable steels. In the

lower grades of steel, the solidified ingot is placed in the furnace or soaking pit so that the ingot may be uniformly cooled until it has reached a semi-plastic but solid state. In rolling, all weldable imperfections or defects in the steel will be united by welding.

In pouring high grade tool, alloy or high speed steel ingots, great care must be taken to cool the surface slowly, otherwise in sudden contraction the surface will tend to crack transversely. This is explained in detail under warping. These steels are dense, hard and brittle in the cold state.

### *Grading the Ingots*

The quality of steel depends upon the method of manufacture, the analysis of the base materials and the method of handling and treating when shaped. When of almost identical analysis, crucible and electric steels take first rank for quality and open-hearth and Bessemer come next in the order named. The quality of crucible steel depends upon the nature of the raw material entering into the crucible mixture. In general, the lower the percentage of sulphur and phosphorus, the better the quality of the steel; and the higher the carbon, the greater is the bad effect of these undesirable elements. The degree of carburization is often referred to as the "temper" of an ingot. In works making thousands of small ingots per day, it would be manifestly impossible to analyze each ingot for carbon. Fortunately, this is not necessary as a very small difference in carbon so changes the fracture, or crystallization of the ingot that the skilled inspector can detect with the eye a difference in carbon of two or three hundredths of one per cent. The ingots, after they are cooled, are always graded by the appearance of the fracture, made by breaking off the upper part of the ingot. The ingots are all put away in a pile with others of like appearance in fracture. Chemical analyses of such piles are usually made of a few of the ingots, particularly so in the better qualities of structural and tool steels. The presence of a large amount of tungsten, chromium, molybdenum, and other alloying metals interferes with or precludes entirely the estimation of carbon with the eye. In determining the suitability of alloy steels for a given purpose, it is necessary to chemically analyze them for all the alloys.

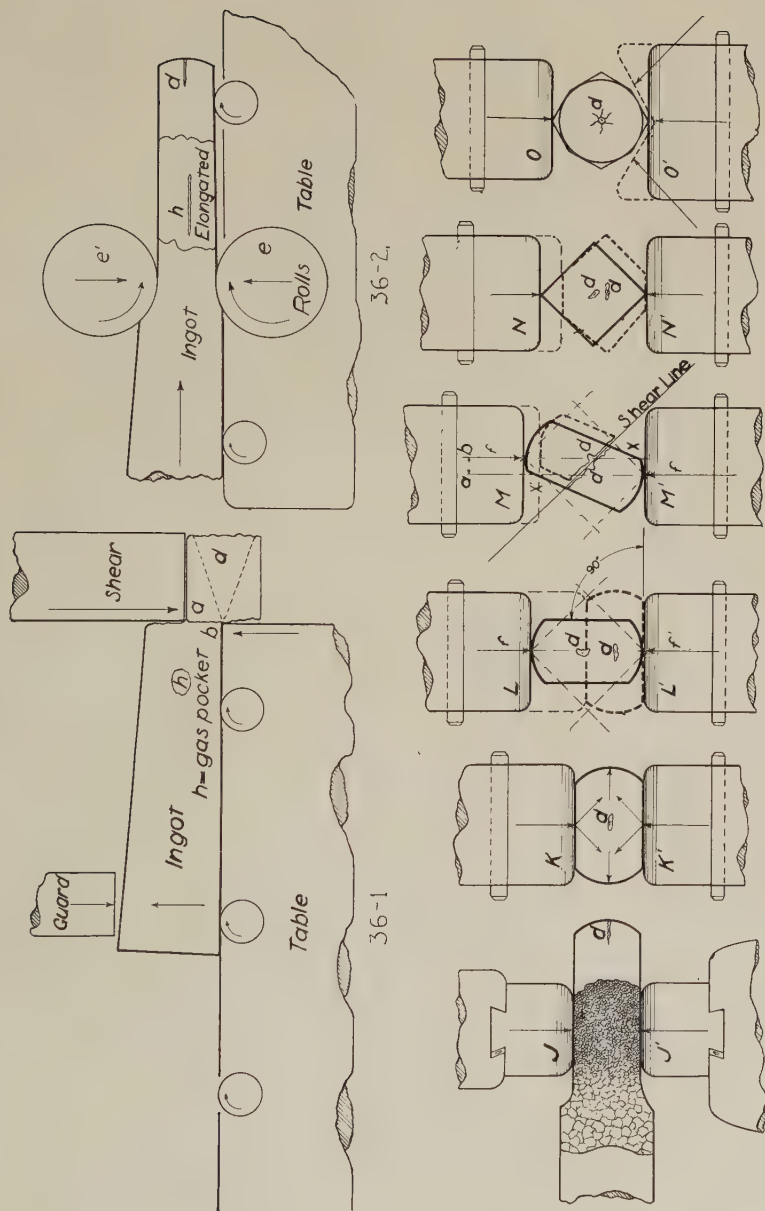


Fig. 36- Illustrates the Effect of Shear and Compression in Rolling and Forging Operations.

## MECHANICAL TREATMENT OF INGOTS

*Rolling or Hammering of an Ingot*

There are several purposes to be attained in the rolling or hammering of iron or steel, (1) to weld and close all defects or voids in weldable metal, (2) to close and elongate all voids in unweldable steel (an unavoidable evil), (3) to form the metal to the commercial shapes desired, (4) to prevent a large crystalline structure, and (5) to increase its strength and other physical properties.

In mill and forge shop practice the first three purposes are the ones usually given consideration. In these operations there may be other defects created even in a perfectly solid ingot or billet. Therefore, to note the effect of shear or compression in the above procedure let us follow a low carbon steel ingot from the removal of the mold, while still hot, to the soaking pit where it is to be heated to a uniform temperature, perhaps to a welding heat and then to the rolls illustrated in Fig. 36.

The hot ingot is moved along the table to the shear where the pipe, Fig. 36-1, d, should be all cut off as indicated. This metal is sheared or cut off for the reason that the force "a" and reaction "b" are not directly opposite but are passing by one another, this action resulting in shear. The ingot is then passed on to the roll "e' e," Fig. 36-2, where it may be noticed that these rolls are diametrically opposite and perpendicular to the horizontal ingot, therefore, compression takes place with the metal flowing along the horizontal. In its second and following passages through the rolls the ingot must be turned through 90 degrees or a quarter turn. If the metal is in a weldable state after the second pass, all weldable defects may and should be welded, otherwise such defects will be elongated parallel to the direction of rolling or hammering.

If all of the pipe end "d" has not been removed in the shearing operation, the defect will remain in the center of the finished product, even to the drawing of a fine wire. The pipe is a starting point for internal rupture, caused from shearing action in rolling or forging operations, especially in rolling or forging polygons and rounds.

Deep-seated blow holes or gas pockets will have the same effect unless they are welded, a possibility in weldable steels but a

practical impossibility in some of the hard and brittle unweldable alloys such as high speed tool steel. The greater portion of alloy or high speed steel is forged to shape under steam hammers or hydraulic squeezers between flat dies. The process makes a very efficient material, if the ingot has none of the defects mentioned and when handled with care and intelligence in its reduction.

One of the most important factors in the drawing down of metal between flat hammer dies is to see that the faces of the dies are parallel with one another at all times and that sharp corners on the edges of the dies are eliminated. The ideal condition is illustrated at J and K, Fig. 36.

If the hot ingot is placed between the dies JJ' and a blow of the hammer or pressure is applied, the metal will flow in a horizontal plane in proportion to the plasticity of the metal and to the amount of force applied. If the hammer is heavy enough or the force sufficient to penetrate to the center of the mass, the bar will elongate as indicated in JJ'. The metal will also spread as indicated in the cross-sectional view KK'. The convexity of the ends and sides of the bar as indicated are probably due to the plasticity of the metal, the amount of force and the retention of the surface metal by friction of the bottom and top dies.

A light blow or too light a hammer pressure will have the opposite effect in drawing the surface of the metal only. The appearance of the bar will indicate this condition of affairs by sharp corners on squares or rectangulars. In other sections the ends of the bars will become more or less concaved. While light blows or pressure have their disadvantage in not moving the center of the metal, they also have considerable advantage if used intelligently.

The next operation and further movements of the stock in its reduction must be given serious consideration. The stock must be turned so that the sides will form an angle of 90 degrees with the face of the dies indicated at L. Let us consider the reason for placing it in this particular position. The object in the reduction of iron or steel by rolling or hammering is to unite all imperfections by welding, close all voids, reduce it to the commercial shape desired and impart a fine crystalline structure to the metal. All of those conditions can only be accomplished by drawing the metal in compression at all times. Therefore, if the stock is placed in the position indicated at L and pressure applied while in that

position every particle of metal will be under compression and if in a welding state all horizontal seams only may be united.

By a careful study of the figure at L it may be noticed that when the force "f" is applied, reaction occurs from the bottom die "f'" and as a force will follow the lines of least resistance, it is quite natural to expect the metal to flow along the horizontal plane. This operation is continued, using a heavy blow until the metal is reduced to near the size required, then the force of the blow is diminished in order to fill out the corners and finish by smoothing up the surface. If there are no previous defects in the ingot, none will be caused by this operation.

On the other hand if the metal is placed in the position M, one of two things will happen. The metal will either slip or roll if in a plastic stage. If the steel is slightly rigid from low temperatures or if we forge a hard alloy or unweldable high speed steel, shear will undoubtedly occur. It may be noticed, (1) that the sample of steel does not form a right angle with the face of the dies, (2) that the forces "f" and reaction "f'" are not diametrically opposite, (3) that the metal would seemingly slip or shear between perpendicular lines "ab" but such is not the case.

As before stated, force will follow the path of least resistance. As the shear line indicated at M is the weakest point the metal slips or shears along that line indicated by the heavy broken line in the figure, particularly so if defects "h" or "d" in the ingot are present and unwelded. If the metal is in a very plastic or weldable state it will flow in the direction of X and X'. Such continuous movement of the metal is not conducive to compressing a sound forging or to the uniting of defects, but causes the separation of that portion which may have been welded and even separation or splitting of a perfectly sound bar.

The figure M is somewhat exaggerated to demonstrate the movement of the metal bar. Such complete actions do not take place unless the metal is constantly rotated and in shear but such action does occur at the weakest point of the stock, usually the center.

If the mass is drawn square in section to the size desired then by using a light blow or pressure an octagon may be formed without moving the center mass. The octagon may be continued to a cylindrical section without causing the center to become spongy,

hollow or sheared. The design of bottom die in O prevents the described shearing action. Under the heading of forging, these points will be further illustrated by actual experiments.

It is assumed that the ingot after stripping, was removed to the soaking pit for uniformity of rolling or hammering temperature and continuously rolled or hammered to the finished product. This procedure, in the writer's estimation at least, is ideal for several reasons: (1) from an economic standpoint in the saving of energy, (2) by the reduction and perhaps the elimination of surface and internal ruptures due to rapid cooling and reheating of such mass, especially that of hard and brittle alloy steels.

### *Reheating of Cold Ingots or Billets*

In attempting to trace some of the causes for internal fatigue, the writer feels safe in tracing the real cause back to the reheating of the ingot or billet in the mills or forge plants where such metal is reheated. Why? Because of the usual process of too rapid heating in order to increase production. Many heaters have little conception of the effect upon the interior of the mass. Their sole object is to get the metal in a forgeable state in the shortest possible time without actually burning the edges or melting the surface. All forge men desire the metal in its softest possible state because it requires less effort to fabricate it. With these points in mind let us trace some of the possible evil effects from too rapid heating: (1) metal will only absorb heat at a definite rate of speed, (2) when heat is applied to the surface of a mass it must expand, (3) iron and steel, depending upon the percentage of alloying elements, methods of manufacture and final treatment, have a definite strength at atmospheric temperature, (4) most all of our commercial steels retain such strength and in fact most of them develop increased strength at about 650 to 800 degrees Fahr. It should now be a simple matter to conceive of the possible effect upon the adjacent cold and weaker section by starting at least a microscopic transverse rupture which may be aggravated in the rolling and forging operation. This may be the reason for the Safety Council requiring that "no ingot of steel allowed to cool to atmospheric temperature be thereafter reheated and rolled into a railroad rail."



In the reheating of our present type of high grade alloy steels the manufacturer will not be responsible for internal rupture unless a definite time is allowed for the reheating of their product. If the temperature difference between the heated surface and the cold adjacent metal exceeds 250 degrees Fahr., the heated surface sets up a fibre stress of about 50,000 pounds per square inch. Therefore such an expanded surface exerts unusual stress on the cold brittle metal, particularly in the initial heating up to 650 degrees Fahr. and may cause internal rupture.

If this advice is followed not alone in heating the metal, but in the reheating of any kind of metal from a cold state, ruptures blamed upon bad steel will be greatly reduced. This matter will be touched upon in the various operations because of its extreme importance in reheating any mass of metal.

Crystallization (so-called), or grain growth, in metal is also a very important phase of the subject. Therefore, in order to assist in illustrating the causes for such conditions in rolled bars of iron and steel the following suggestions and Fig. 37 are introduced.

#### THE EFFECT OF REHEATING, SOAKING, AND ROLLING

##### *Upon the Crystalline Structure of Steel*

It has been previously stated that iron and steel are crystalline solids. The size of such grains or so-called crystals depend upon the chemical elements combined with the iron. The elements present and the factors, temperature, time and work (hammering or rolling) accelerate or retard grain growth. Fig. 37 is a graphical illustration of the various changes in structure that may be developed, depending upon these factors. Fig. 38 shows an ingot being rolled. Fig. 39 shows a heavy ingot being forged under a hydraulic press.

It may be noticed by following the line of circles "a" parallel to reheating curve "b" that the size of the grains (circles) remains constant until the metal attains a temperature above the highest point of the critical range  $Ac_3$ , (we are assuming in this case a very low carbon steel) at which temperature a molecular transformation occurs, breaking up all pre-existing coarse structure in any part of the metal attaining that definite temperature. When



Fig. 38—Rolling an Ingot.—Courtesy of Bethlehem Steel Company.



Fig. 39—Forging a Heavy Ingot.—Courtesy of Bethlehem Steel Company.

this physical change occurs, a new grain is born as indicated by a breaking up of the large size grain (circle) into a very small one just above the line A or  $Ac_3$ . For a given type of steel, this change occurs at a definite temperature only. Time is therefore an important factor in changing the structure of a large mass.  $Ac$  refers to the critical temperature on heating and  $Ar$  to the critical temperature on cooling.

This change in structure is the ideal desired in all methods of treatment. But unfortunately the metal at this temperature is not sufficiently plastic for forging purposes, therefore it is necessary to heat the metal to a higher temperature that it may become soft and plastic enough to be rolled with less energy and fill the sections of various fabricated shapes, etc. The maximum temperature to which metal may be heated is just below its melting point. However, heating above the critical range causes grain growth as indicated by the gradual increase of size of circles above the horizontal of line A. The higher the temperature, below the melting point, the greater the opportunity for migration and coalescence of crystal matter. Therefore, larger grains may be expected if left undisturbed in cooling.

Soaking, or time, is important at any temperature the metal may be heated to, because of the necessity for uniform temperature throughout the mass. Otherwise the metal will not flow uniformly under the hammer or roll to fill shapes of dies. Soaking also further increases grain growth as indicated on the horizontal line of circles, Fig. 37. Therefore, unnecessary soaking is not alone a waste of time and energy but is not conducive to development of high grade metal from a grain size standpoint at least. This is illustrated in the unworked end of the ingot, billet or bar in process of rolling.

There are three purposes in rolling, (1) shaping the metal as desired, (2) welding defects, and (3) imparting a fine structure to the finished product. Let us follow the line of circles "d" downward. By continually working the metal we will break up the original large structure and by the same means we will prevent further grain growth as indicated by the smallest grains at the  $Ar_1$  point, at which point crystallization ceases. This is further illustrated by small grains directly between the rolls.

If work stops at the point "f" on the line of circles "d" the

metal is still above the temperature at which crystallization ceases and an opportunity is given for further grain growth as indicated by projecting grain "f" to "e" and following the line of cir-

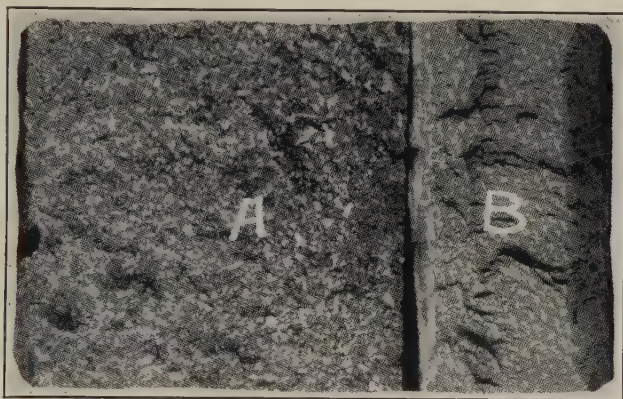
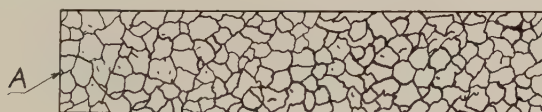
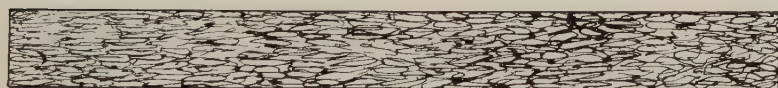


Fig. 40—Shows the Effect of Forging or Rolling at High or Low Temperatures. See Text, Page 60.

cles "e" downward. In the central figure of metal between the rolls, that part of the metal to the left has not been worked and



Grains before cold drawing



Grains after cold drawing



Grains return to normal size after annealing

Fig. 41—Illustrating Annealing After Cold Working to Remove Stresses. A Shows Grains Before Cold Working, B After Cold Working, and C After Annealing.

metal on the right has been partially worked. Defect "h" is an elongated seam of unweldable steel.

Changes of the metal in cooling through the critical range have

been explained. The cause for large size grains or crystals should be fairly well understood. The size of grain in the usual rolled or hammered bar stock as purchased by fabrication plants will depend upon these factors. The grain size as a rule, will not change the chemical composition of the metal. To further illustrate these points a small test block was allowed to cool to atmospheric temperature and ruptured, shown in "a," Fig. 40. One-half of the bar was hammered as above indicated and broken as indicated at "b" (illustration full size). Half "a" was heated to forging temperature but was not worked. From this, one can see that the usual hammered or rolled mill stock, when ruptured, may show grain size in proportion to the amount it has been worked and the temperature at which the metal was finished.

### *Mill Annealing*

In the manufacture of high grade tool, alloy and high speed steel the next step is the process of annealing. Its purpose is to attain machinability and uniform structure. This is accomplished by heating to above the critical temperature and holding at that temperature for some time, then allowing the steel to cool slowly. The changes that occur will be explained in detail and illustrated under heading "annealing." This process may create a surface defect known as decarburization, signifying the removal of the carbon from the surface of the bar. In the decarburized layer, the metal gives up its carbon, returning to its base, soft iron as was explained under the effect of free oxygen upon heated metal.

### *Cold Work*

Cold working of metal imparts greater strength and gives the metal a high surface finish as in cold rolling or drawing. It produces a section accurate in size with increased strength, elastic limit and hardness accompanied by an increase of brittleness.

In the rolling or hammering of metal above the critical temperature we learned that the grains are broken up and due to the plasticity of the metal the grains tend to grow and to assume their natural position. Pressure hammering or squeezing below the critical or at atmospheric temperature does not as a rule break up the grains but distorts them by elongation in the direction of work, and owing to the rigidity of the mass the grains do not return to their former unstrained position, shown at B, Fig. 41.

## LECTURE II

### MECHANICAL WORKING OF IRON AND STEEL

After a bar is rolled it is often forged or cold-worked to the shape or form required. This may involve one or all of the fundamental principles of forging, such as cutting the metal to convenient lengths (shearing), reducing its cross section (drawing), shortening its length with increase of cross section (upsetting), deflecting the metal from a straight line around its own axis for alignment (bending), heating the metal to a welding state and uniting by pressure such as hammering (welding), and heating to bring out certain physical properties of the metal (heat treatment).

While there are many sub-divisions of these operations in the manipulation of the metal, one or more of these principles must always be applied. We shall now attempt to explain the proper procedure in production and particularly the causes for defects in the various operations. If conversant with the causes for defects many errors may be avoided.

These operations will be taken up in sequence. The first operation is cutting the stock to convenient length by one of the following tools: (1) shear, (2) chisel, (3) hack saw, (4) oxyacetylene cutting torch. All soft iron or low carbon steels can be and usually are cut by method 1, without serious injury to the material, owing to its high degree of ductility. On the other hand, all brittle high carbon or hard alloy steels should never be cut by method 1. By referring to Fig. 42, it may be noticed that the shear blades "a" and "c" have a tendency to crush the ends of the stock in the shearing operation, and may create an incipient fracture adjacent to the blades, thereby causing a transverse defect in the finished forging. Methods 1 and 2 can be used for cutting brittle high carbon steel only when the metal is heated above a red heat. An efficient method of cutting soft steel is method 3, which produces no defect whatever in the material. The harder steels must be in the annealed state to be cut by a hack saw.

We have seen that ingots are cast from molten steel. The ingot may vary in size from a few hundred pounds to a hundred

thousand pounds. As poured, an ingot is a "raw" product, large grained and too large in size to be useful in that form. Mechanical work is required to break up the large grain structure and to form the ingot to the desired shape. The first operation is to "cog down" or "bloom down" the ingot by rolling to elongate it. The product of the blooming mill is cut by the hot shear or saw into convenient sized blocks termed "blooms." The blooms are then rolled into bar or structural shapes in another mill.

If the ingot is to be formed into a large forging, it is squeezed to approximate size in a hydraulic press, then reheated and further

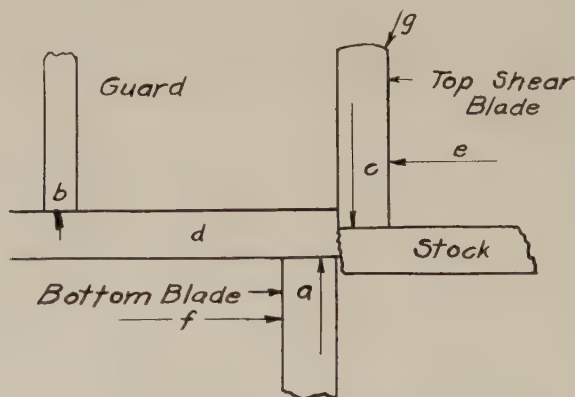


Fig. 42—Illustrating the Action of Shearing Off or Cutting a Bar of Stock in a Mechanical Shearing Tool.

worked. All mechanical work must be performed within certain temperature ranges for each steel, to avoid overheating the metal or working it at such a low temperature that the metal is no longer plastic. The proper sequence and temperature of operations should be given careful consideration to avoid waste.

### *Cold Working.*

There is a limit to the amount of distortion by cold working because of the danger of separation or rupture of the natural cohesion between the grain boundaries. It is the cold work or distortion of the grains that causes hardness and brittleness and therefore, such metal is under severe stress. If further reduction is necessary the stresses may be relieved by annealing the material at a temperature just below the lowest point of the critical range,

$Ac_1$ . Such treatment causes the grains to return to their normal position previous to being stressed. This treatment allows further reduction. Annealing of cold rolled or drawn metal removes the strains imparted in cold working and the grains revert back to approximately their former shapes. Fig. 41 shows schematically the effect of annealing to relieve cold working strains. A shows the unstrained grains, B shows the elongation of the grains due to cold working and C shows restoration of the grains after annealing.

There are many other mill practices that would be of interest but the scope of this book will not permit. We hope, however, that the three important types of material used in the fabrication of machinery parts and tools—the usual bar stock, forgings and annealed and cold-worked stock will suffice.

### *Heating*

While some of the softer metals can be formed to advantage in a cold state, considerable power is required for such an operation. Hard, brittle steel cannot be cold formed except in machine cutting operations. Hard metals are heated so that they may be formed into the various shapes while hot, thus avoiding serious defects in the material. Hot, plastic metal will require less energy or power in its shaping and working.

The object in heating is to soften the metal to a semi-plastic or even a welding state so that it will work or form freely in reduction under the hammer and fill the impression in forging dies, etc. The metal should be heated slowly and uniformly throughout its entire cross section to about 100 degrees Fahr. below its burning point (the burning point of a steel depends upon its percentage of carbon). It is then ready for forging. Great care must be taken in the heating operations, especially in high carbon or hard alloy steels, in order to prevent any defects being formed by the uneven expansion of the metal. Quick heating of high carbon or alloy steel from ordinary temperatures to a high temperature may cause internal cracks or ruptures from sudden expansion of the quickly heated surface. Likewise, if the temperature is above the burning point of the steel the corners and surface of the metal may become badly burned, and therefore, hot-short in the forging operation, a condition which no amount of work or heat treatment

will rectify. A soaking heat close to the burning point after the metal is uniformly heated may cause the mass to become hot-short and brittle, i. e., when struck a blow with a hammer it will crumble or disintegrate.

Many hammer smiths will hold burned metal in the air until the temperature has been lowered below the temperature at which it crumbles, then attempt to weld it together. While possible in weldable steels, such procedure is not at all desirable as a welding treatment will cause such metal to become cold-short, i. e., it fractures easily under bending stresses. As a rule the surface of such metal does not indicate the true condition of the center of the metal, therefore, the scrap pile or melting furnace is the most desirable place for cold or hot-short material.

The grain structure is greatly affected by continued working of the metal as it cools from the high temperature necessary for forging or welding operations. Proper cold working may improve its physical properties. Let us carefully study the diagrammatic illustrations in Fig. 37, remembering the effect of rolling or hammering upon the structure of a steel ingot. We have the same condition of grain structure to contend with in mill stock when it is heated to a high temperature regardless of the previous amount of mechanical work (hammer or rolling) or heat treatment. The effect on grains due to continued hammering down to the lowest point of the "critical range" is illustrated in the fractured sample, Fig. 40.

### *Drawing*

In drawing out a piece of metal under the hammer, it must be pounded into definite shapes, and pressure and force must be applied intelligently. Of all the various methods of producing finished metal products the greatest care must be used in drawing because of its effect upon the more or less inherent defects of all steels. Reducing the cross section and correspondingly increasing its length reduces and elongates such defects in proportion to the amount of reduction. In reduction the metal is usually formed into four general shapes, and in the order given: (1) square; and (2) from this shape to a rectangle; or (3) from a square to a polygon; and then (4) to a round. The proper procedure for drawing such sections is illustrated diagrammatically in Fig. 36,

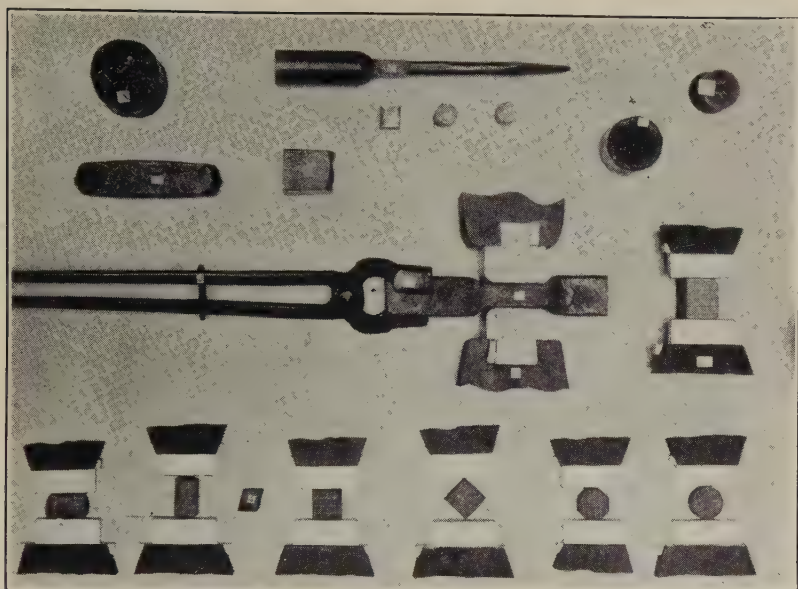


Fig. 43—Illustrating the Steps in the Reduction of a Short Square Bar to a Longer, Round Bar.

but to further emphasize the actual movement of metal under pressure the following experiment is introduced so that the reader may better see the reasons for this procedure. The proper procedure in reducing iron or steel from a larger section to a smaller one, and therefore to the shape desired, is outlined in Fig. 43. Machine a number of the small pieces of steel on the ends and mark in the form of checker work or square blocks as shown in Fig. 43. The hammer guides are carefully inspected and tightened to prevent lateral movement and the dies planed parallel with each other to insure true movement of the metal while under compression. One end of the block is heated to the usual forging temperature and placed upon the bottom die as indicated at "a", Fig. 44. If the reader will consider those small squares as a pile of bars of iron or steel to be welded together, rather than a solid mass of steel having no internal defects, he may have a clearer conception of the idea the author wishes to convey. How many of our brick

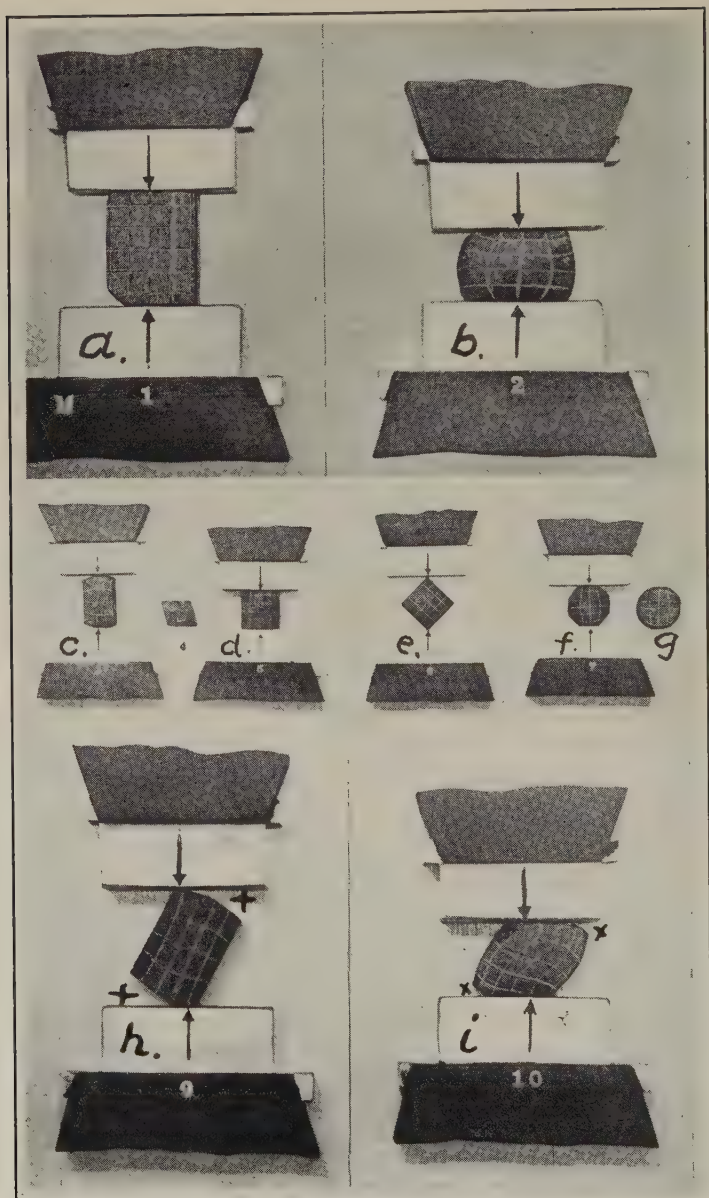


Fig. 44—Illustrating in Detail the Procedure for Reducing a Square to a Round Section Under the Forging Hammer.

and stone buildings would remain standing if the brick or stone were not laid level and plumb? What would be the result if the material were laid otherwise? Keep the possible results in mind during this discussion.

If pressure or a blow of the hammer is applied to the metal while in position "a" each imaginary block will sustain the load of the one above it, and if the metal is sufficiently plastic or weldable, it will flow in a horizontal plane (because that is the path of least resistance). All horizontal seams should be welded by the hammer blow, and probably the vertical seams will be partially welded due to the flow of the metal in a horizontal plane. This is clearly indicated at "b". The convexity of ends and sides show that sufficient pressure was applied to move the entire mass. The convexity is probably due to the friction of the top and bottom dies which prevents the metal from flowing in contact with them. The block "b" is repeatedly turned as indicated at "c" so that the sides will always form a right angle with the face of the bottom die or anvil. In this manner the metal is reduced to a square having the cross sectional area desired and indicated at "d". With this procedure the metal will always be in compression, therefore all horizontal and vertical seams should unite by welding (if the material is weldable). This operation will not, as a rule, distort inherent defects or cause internal rupture. It may be noticed that the position of the marked lines has not been disturbed to any appreciable extent in this reduction. This method is recommended as the proper procedure to be followed in reducing all shapes, at least to the area of the cross section desired. The next step in drawing is to form an octagon and then a round section.

It may be noticed in Fig. 44-d that the steel has been drawn to a square of the same area as the octagonal (eight sided) section "f". Octagon "f" is reduced to round section "g" without changing the location of the marked lines to any appreciable extent. In forming the octagon, two points of the square are placed perpendicular to the plane of the hammer die and only sufficient force applied to form to shape without disturbing the center of the stock as indicated at "f". Likewise, in drawing the round from the octagon, a few light blows are necessary to break down the eight points of the section, with still lighter blows

on the sixteen points in order to complete a true round section without disturbing the center mass as indicated at "g". This procedure applies to forging these shapes between flat hammer dies or on the anvil with flat hammer tools.

The cause of defects in drawing any section is often the improper placing of the metal under the dies when compression takes place. When improperly placed, the metal is usually in shear. Hammermen or blacksmiths in reducing metal to a square

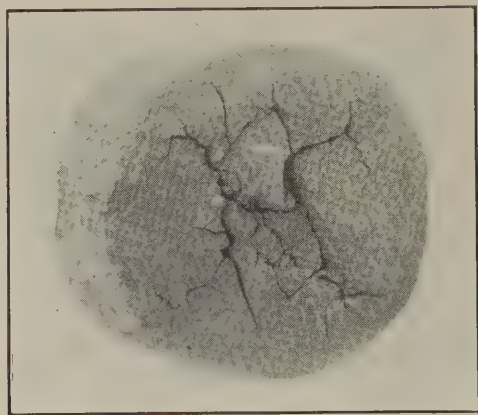


Fig. 45—Failure in a Forged Round due to Repeated Shear Under the Hammer in Reducing it from a Square to Octagon, then to Round.

section often tend to place the metal so that the die faces are not perpendicular as to the side of metal. The result of such carelessness is that the metal becomes more or less diamond-shaped on the first few blows of the hammer. This condition of affairs is often noticeable among drop forge hammermen in their breakdown work. Let us now consider the effect of placing the metal in any other position between two flat dies. To demonstrate the effect, place the metal as indicated at "h", Fig. 44. The metal will follow the path of least resistance and flow at the points "xx". This flow of metal is clearly demonstrated at "i" in which the two vacant spaces "xx" are now filled. By observing the curvature of the vertical lines at "i" it may be noticed that they are badly bent and from the position of these lines it is self-evident

that the upper portion of the metal has moved to the right and the lower portion has moved to the left. Is it not self-evident that there must be a tearing action or at least some slippage taking place somewhere between those two movements of the metal? Such slippage will, of course, occur along the lines of least resistance, usually termed the "shear line", line "xx" at "i". Constant reversal of this deformation may cause final failure, as is shown by the photograph Fig. 45. The rupture is due to the metal not being forged in compression but in repeated "shear".

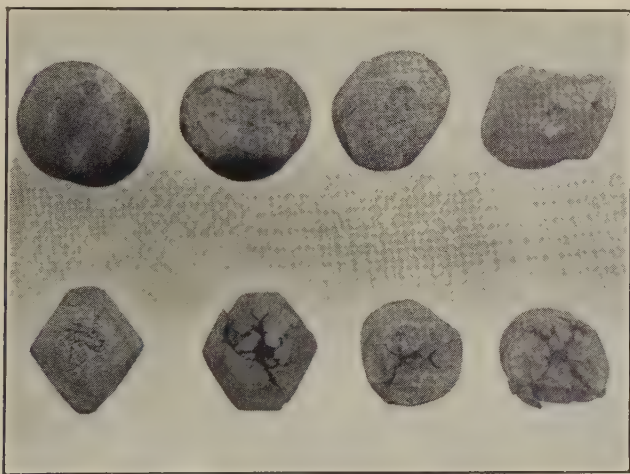
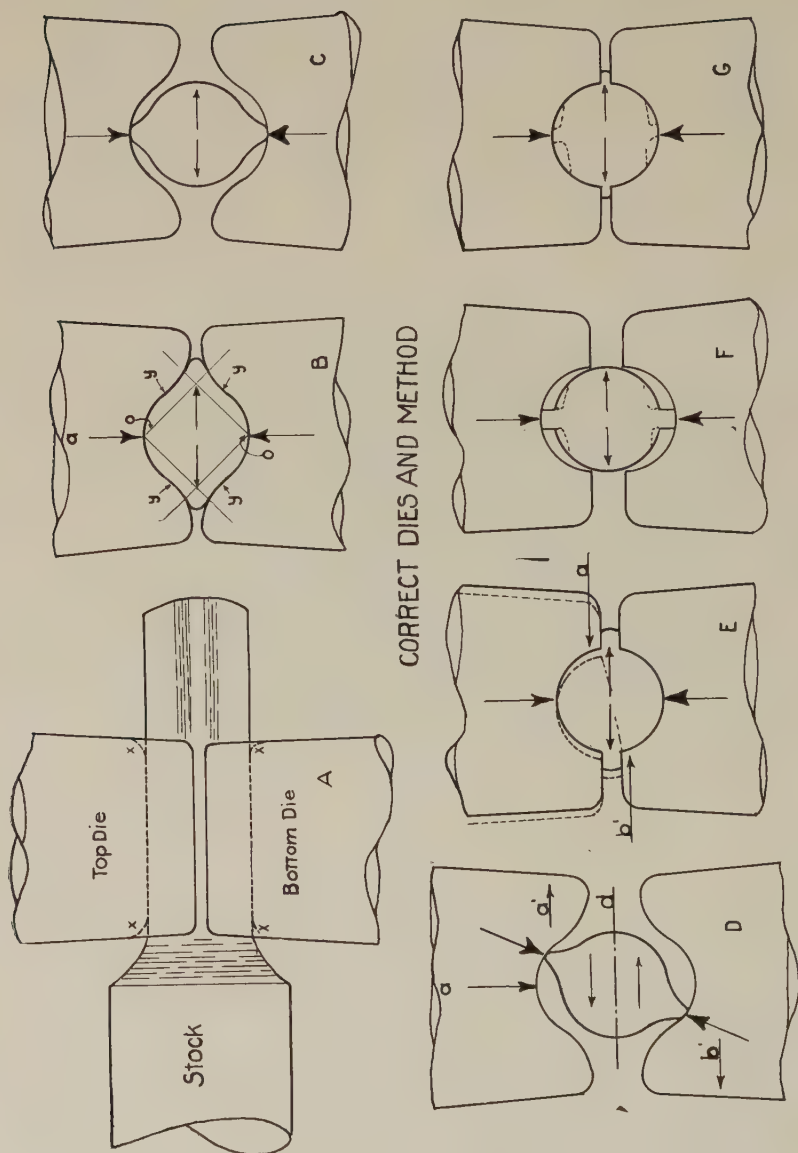


Fig. 46—Illustrating Attempts to Forge a Smaller Round Section from a Large Round Bar without First Forging the Bar to a Square, then to the Desired Round.

### *Drawing of a Round Section*

If a hammerman or blacksmith is asked to reduce a large round section of iron or steel to a small round, he will usually rough it down fairly square in section, considerably larger in area than the finished round. He will then attempt to form the round section by constant rotation between the dies. Many workmen try to maintain the metal in a partially cylindrical form and reduce the section by constant rotation between flat die or swages. Even with small bars, this method may easily cause the bar to become hollow at its center with numerous small shear lines radiating from the center. When this condition is found in round sections



INCORRECT METHOD AND DIES

Fig. 47—Showing Methods of Swaging Round Stock,

it is often attributed to other causes such as "pipe," poor grade of metal or that it is hammered too cold. This may be true, but it has been proven, to the writer's satisfaction at least, that a cold piece of iron or steel can be reduced in size without destruction by shear provided the metal is first drawn square in section and reduced as shown in Fig. 44. Possible results of the last named method are indicated in Fig. 46, where it may be noted that each of the shear lines indicate the movement of the metal in its rotation under the hammer. It may also be seen that the surface of the stock does not indicate the cracked condition of the center.

### *Swaging to a Round Section*

The impression is held by many blacksmiths and hammermen, that the use of "swages" in forming rounds from square sections practically prevents the danger of internal shear cracks. Fig. 47, A-B-C illustrates the correct form of dies and the proper position of holding the metal between them in all forging operations where the metal is turned or rotated to form a round cross section. Note that all sharp corners of the dies are rounded for the purpose of preventing "cold shuts" and flaws in its reduction. Cold shuts are caused from overlapping of the metal when worked below a welding temperature. The round corners "x" in A and "y" in B will form "fillets". These may be swaged down without the danger of overlapping, or causing "cold-shuts" as the metal is drawn back and forth or turned. The curves at "o" in B show the finished shape of the stock, and form the arc of a circle when the dies are closed. It will be noticed that the points "y" in B give the surplus metal freedom to move in a horizontal plane.

The next position of the stock is shown at C. All subsequent positions are of vital importance in its reduction to the size and form required. The two long points formed in operation B must be turned through 90 degrees, similar to the drawing of a square section. This will place the stock with the two long points in a vertical position. If pressure is applied while in this position the metal will be under compression and will flow in a horizontal plane as shown at B. If this operation is continued until the dies are closed or touch one another, the metal will be under compression at all times and no defects will be introduced. If

the stock is misplaced in the dies so that the long axis of the section is not vertical, it will cause a severe side strain to the bottom and top die. This is one of the real causes for the loosening up of the lower die keys. It will also cause unusual stress on the hammer guides, indicated in D at "a<sup>1</sup>" and "b<sup>1</sup>" and will cause a reverse horizontal movement of the metal above and below the line "d". If this action is continued it may lead to a hollow center caused by internal shearing of the metal. Many workmen do not realize the disadvantage of this procedure, but claim the stock is of poor quality if it should split in the operation.

The dies E, F and G are imperfect in form. In their use defects are formed by the sharp corners which cut into the stock. This is clearly illustrated by the dotted lines, which show the cause for "cold-shuts". Drop forging dies, however, are usually made with sharp corners in the impression as indicated at E, to form a perfectly cylindrical section when the dies are closed. This figure also illustrates the effect of lost motion in the hammer guides which may cause a horizontal shear on the metal after the last blow has been delivered, causing longitudinal seams or a split forging. Note direction of "a<sup>1</sup>" and "b<sup>1</sup>" arrows, and the dotted line indicating horizontal movement which may lead to shear of the stock, especially at the finishing temperature.

#### *Drawing a Rectangular Section*

Here, again, numerous defects are caused by improperly applying the principles of drawing such shapes. A procedure often followed, is shown by an incident occurring in a forging class. Pieces of chisel stock were given to the men with the request that each make an ordinary cold chisel. Ninety-nine per cent of them (unless previously trained) formed the blade too wide, then attempted its reduction.

It is difficult to outline any fixed procedure but the writer has found the following method to be advantageous. The metal should be drawn square in section, the square being one and one-half times the area of the final cross section desired. This dimension will depend largely upon whether the hammer die or anvil be crowned or flat. If the metal is placed parallel with the crown, the metal will spread more and draw less in length. If the stock is placed at right angles with the crown, the metal will elongate more than it will spread. The rectangle should

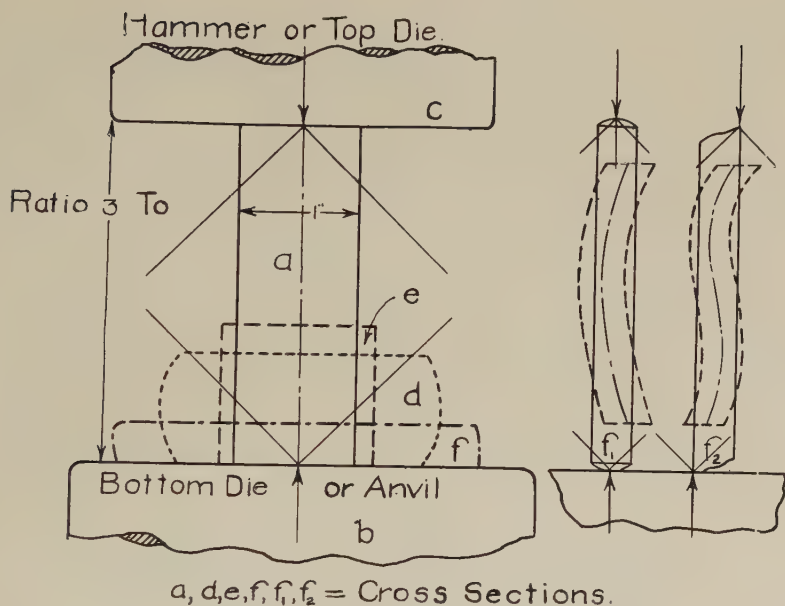


Fig. 48—Method of Drawing Down a Rectangular Cross Section.

be further reduced in cross section by the procedure shown in Fig. 44 a, b, c, and d.

### *Buckling Action of Longer Pieces*

A tendency among hammermen is to spread the stock greatly in excess of the dimensions required, then attempt to reduce it in width by hammering in the direction of the largest dimension (length). Experience has demonstrated that there is a limit to the width of stock that may be reduced in that direction without causing distortion or defects. The limiting ratio of length to width of cross-section is about as 3 is to 1. Fig. 48 illustrates this ratio. If a section of material of this ratio is placed perpendicular to the plane of the bottom hammer or anvil die "b" and if the face of the hammer "c" falls parallel to the face of anvil "b", then the force so applied will cause the metal to assume the form at dotted lines "d". If "a" is drawn square in section as indicated in dotted figure "e", it is a simple problem to spread it to the form "f" and "f<sub>1</sub>" by repeatedly turning it under the hammer. A few light blows will spread the edges of the stock, but if a heavy blow is used to shorten its length the metal will

bend, due to column weakness as indicated by the dotted line in " $f_1$ ". If the edges are tapered similar to " $f_2$ " and force is applied while in that condition we can expect a compound buckle as indicated by the dotted lines in this figure. The effect of bending and straightening will cause a serious defect, illustrated by the photograph in Fig. 49, and more fully explained under upsetting and bending.

There are also a few points regarding adjustment and care of the moving parts and hammer dies in the drawing of any of the foregoing sections, which may cause shear, regardless of the effort of the workmen in performing the operation correctly. First, all hammer dies should be keyed so as to prevent horizontal movement; secondly, guides for the top die should be tight enough to prevent a horizontal movement when the blow is delivered; thirdly, the dies should be maintained parallel (at all times) with

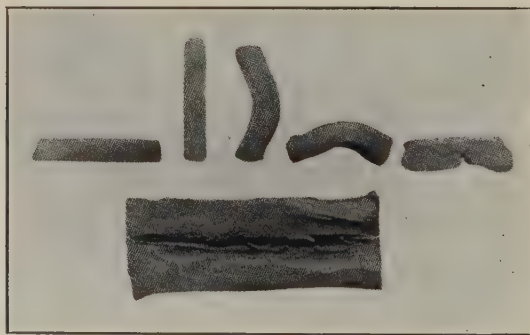


Fig. 49—Longitudinal Rupture Due to Column Action in Forging a Thin Flat Bar.

each other; and fourthly, it is a practical impossibility to draw a true square section and prevent a shearing movement in metal, if the dies become hollow in the center, especially so when the cavity is parallel with the drawing operation. This condition is usually caused from wear of the metal or by pounding scale into the dies.

### *Upsetting*

Of all the methods of manipulating iron and steel in the forging operations, upsetting requires the greatest care. If a specimen to be upset has a ratio between length and diameter

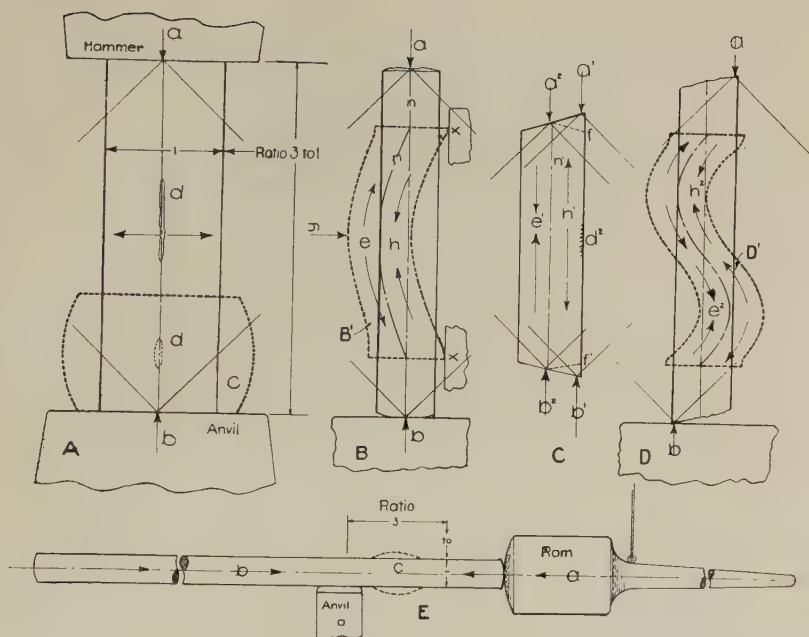


Fig. 50—Showing Distortion that May Take Place in Upsetting.

in excess of 3 to 1, bending of the specimen will occur either in the form of a single or compound buckle. Therefore, the metal must not exceed this ratio of 3 to 1 unless it is braced to prevent bending or buckling in the upsetting operation. Constant bending and straightening in upsetting may cause incipient cracks or rupture even at a red heat. Defects caused in upsetting will be readily understood if we consider the many defects in a bar of steel that may be elongated by rolling or forging operations and the possible elongation of slag between plates of welded iron or soft steel. This condition has been explained in the section relating to the piling of slag iron and defects in ingots. Many of these defects may cause lines of weakness parallel to the direction of rolling or hammering. Upsetting may cause a separation of the material around such defects, due to imperfect cohesion and due to the metal moving in a horizontal direction and at a right angle from such lines of weakness. This is illustrated in A, Fig. 50. This figure also shows the dimensional ratio of 3 to 1 and the proper position of placing the metal between the anvil or hammer dies.



Fig. 51—Showing Defects which May Occur in Upsetting Operations.

If a force such as a blow of the hammer or pressure is applied to the metal while in the position indicated, the metal will upset without bending. This action is possible, due to the strength of the bar and to the metal having equal resistance on each side of the neutral axis or, on center line, "ab". The result of such action is indicated by dotted "c", at A. The elongation of a previously described defect is illustrated at "d," while "d at c" illustrates the possibility of opening up such lines of weakness in the upsetting operation. This operation will also cause an opening up of surface defects, if they exist, as illustrated in Fig. 51. However, if the metal has no defects to begin with, none will be caused by this operation, provided that the bar is maintained perpendicular to the plane of the die. In forging steel gear and other blanks by this process the location of stock under the hammer should be kept in mind so that the so-called fibers may flow in the proper direction.

The disadvantage in upsetting stock where the length exceeds the ratio of 3 to 1 is the bending action due to "column weakness"

illustrated in B Fig. 50. It may be noted that the line of force "a" and reaction "b" are directly in the center of the stock with equal resistance of the metal on each side of the neutral axis. In spite of all these precautions the metal will usually assume a form similar to B<sup>1</sup> in view B and form "column weakness." When bending takes place the neutral line will partially upset, with the

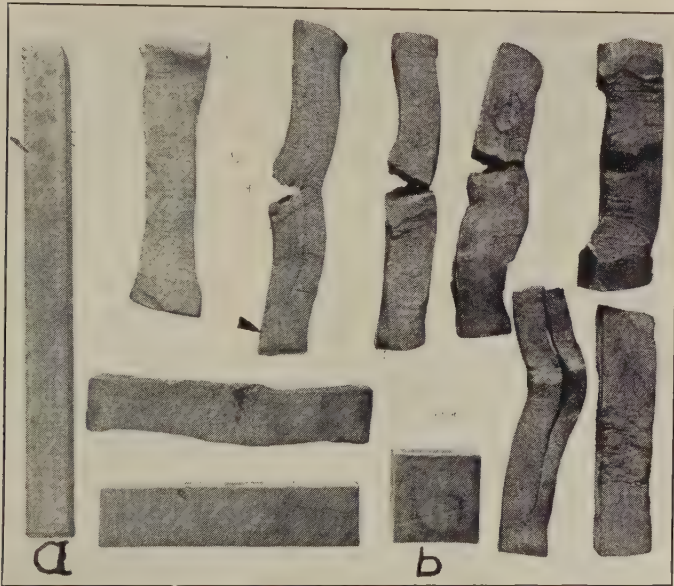


Fig. 52—Showing Defects in Upsetting Due to Column Action.

maximum upsetting taking place to the right of the neutral line "n", indicated by arrows at "h". A reverse movement occurs on the opposite side of the line "n" at "e" where stretching or elongation takes place, increasing toward the left side of the figure.

This action may be likened to that of driving a twenty penny spike or nail into a hard oak board.. It usually bends and before attempting to drive it again it must be straightened. On a second attempt it usually bends again in the same place. Likewise B<sup>1</sup> must be straightened before further upsetting of the entire bar can take place. To do so let us assume that the vertical position of the figure be placed horizontally (turn the figure 90 degrees to the

right). The metal is supported on two points "xx" and force applied at "y". When pressure is applied at the point "y" a reverse movement of the metal must take place above and below the neutral axis, i. e., "h" elongates while "e" upsets. This condition is illustrated in C, with the direction of the movement of the metal shown by arrows at "h<sup>1</sup>" and "e<sup>1</sup>". At this stage of the operation the metal is usually at a low temperature, therefore there is danger of forming small horizontal cracks indicated at "d<sup>2</sup>", (somewhat exaggerated). If the force "a<sup>1</sup>" is again applied to upset this piece after being straightened, it will probably bend in the same place, similar to driving the nail. The bending in this case is due to the force following the lines of least resistance. If buckling and straightening be continued, the bearing surfaces "a<sup>1</sup>a<sup>2</sup>" and "b<sup>1</sup>b<sup>2</sup>" will become distorted from the horizontal, as shown, thus aggravating the tendency to buckle, and tending to further open cracks at "d<sup>2</sup>".

This action may be likened to that of breaking a piece of wire between the fingers. If the ends of the bar are trued up according to the dotted lines "f" and "f<sup>1</sup>" upsetting may be continued, due to the fact that the applied force will again have equal resistance on each side of the neutral line "n". The results of not preparing the ends of the stock properly are further illustrated at D, which condition may cause a compound buckle as indicated by the dotted figure D<sup>1</sup>. If continued upsetting were to take place, without straightening, it would cause two cold shuts at "e<sup>2</sup>" and "h<sup>2</sup>". Fig. 52 shows an exercise given to students at Purdue University to emphasize these points. The students are furnished with a piece of soft steel  $\frac{1}{2}$ " x  $\frac{1}{2}$ " x 5" indicated at "a", and requested to upset it to a perfect cube indicated at "b". Time or space will not permit us to go into details concerning each of the imperfect pieces but sufficient information has been furnished that the reader may easily interpret the results shown.

Long sections may be upset provided that the 3 to 1 ratio is not greatly exceeded, and that the stock is at all times kept relatively straight by means of supports and guides. This is illustrated in E, Fig. 50, showing the ram in position for upsetting. In the production of various parts of machinery such as crank shafts, gears, etc., by the upsetting process, the material must be upset in such a manner that the longitudinal lines inherent

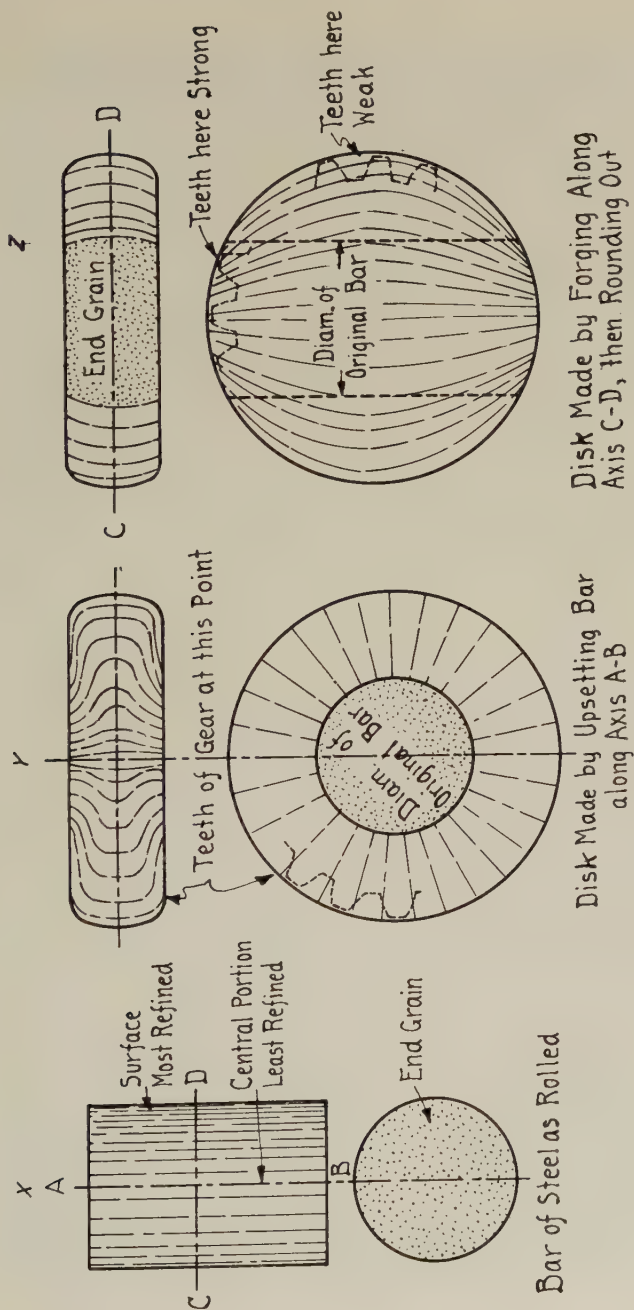


Fig. 53—Illustrating the Correct Flow of Metal in the Upsetting Operation.



Fig. 54—Showing a Gear Blank Cut in Two Through the Center and Etched to Show the Flow of Metal When Upset.

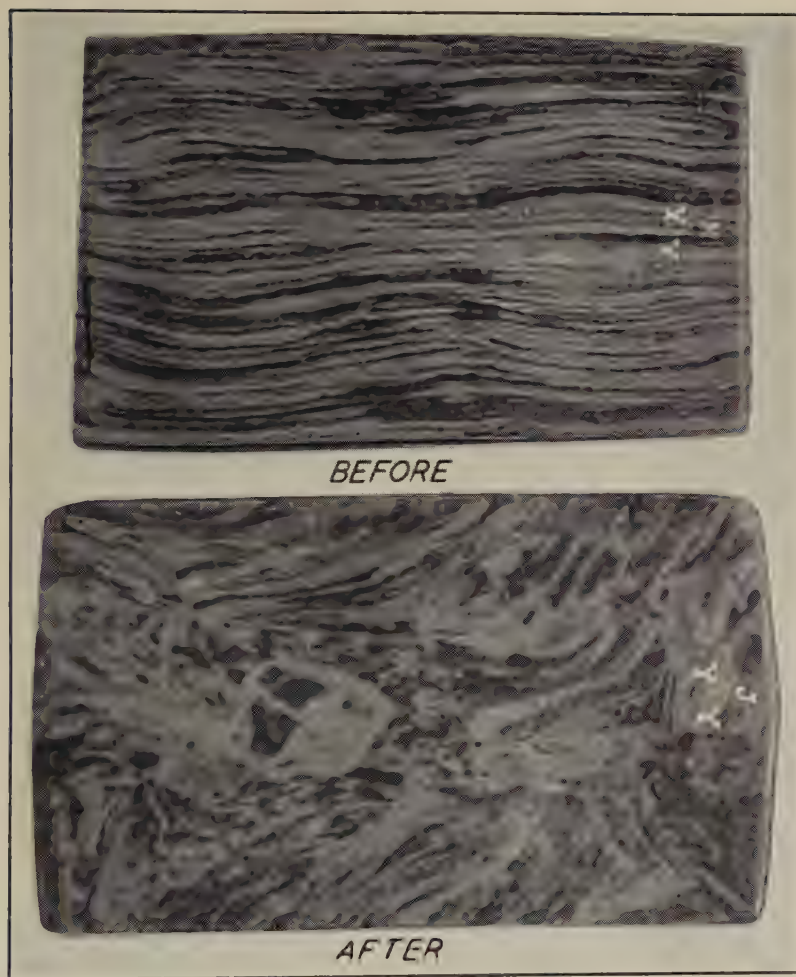


Fig. 55—Illustrating the Improper Flow of Metal in Upsetting.

in metal will flow in the proper direction as illustrated at X, Fig. 53, resulting in correct upsetting indicated at Y. The uniformity of flow indicated at Y is evidence that force at X was applied in the proper direction. Fig. 53, Z illustrates the possible weakness of gear blanks produced by the method of upsetting or spreading and rounding up.

*Etching to Detect the Flow of Metal*

In procedure controlled plants the usual method of detecting the exact flow of the metal in forging is to cut a section in two, polish and etch it with hydrochloric acid for some time in order to bring out the characteristic flow of metal as indicated in cross section of a gear blank, Fig. 54. This is one of the important checks in gear making. The gear blanks are rejected unless the

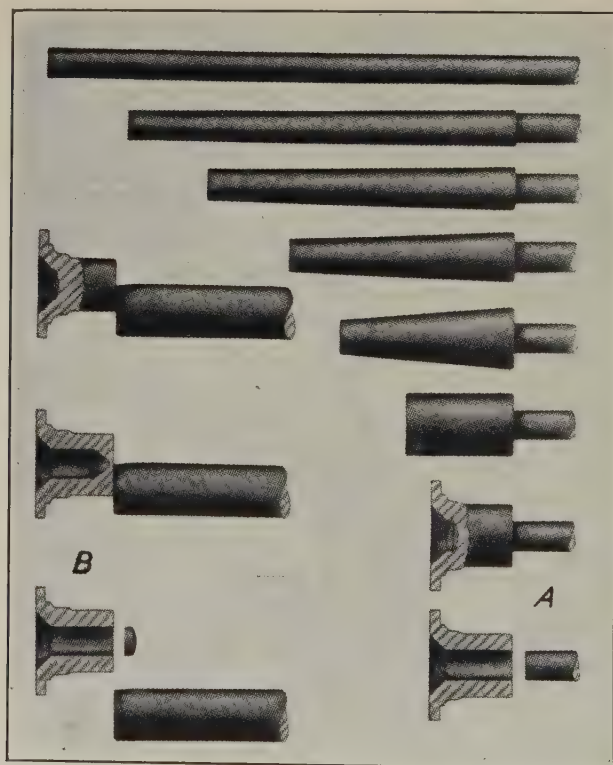


Fig. 56—Illustrating Progressive Upsetting Operations in Forming a Cupped Guide. "A" Shows the Old Method. "B" Shows the Latest Method.

metal flows in the proper direction. Rejections will not occur if the blank is placed under the hammer in the proper position so that the metal cannot flow otherwise than correctly. Fig. 55 shows a case of improper flow of metal in upsetting. Note the irregularity of flow lines after upsetting.

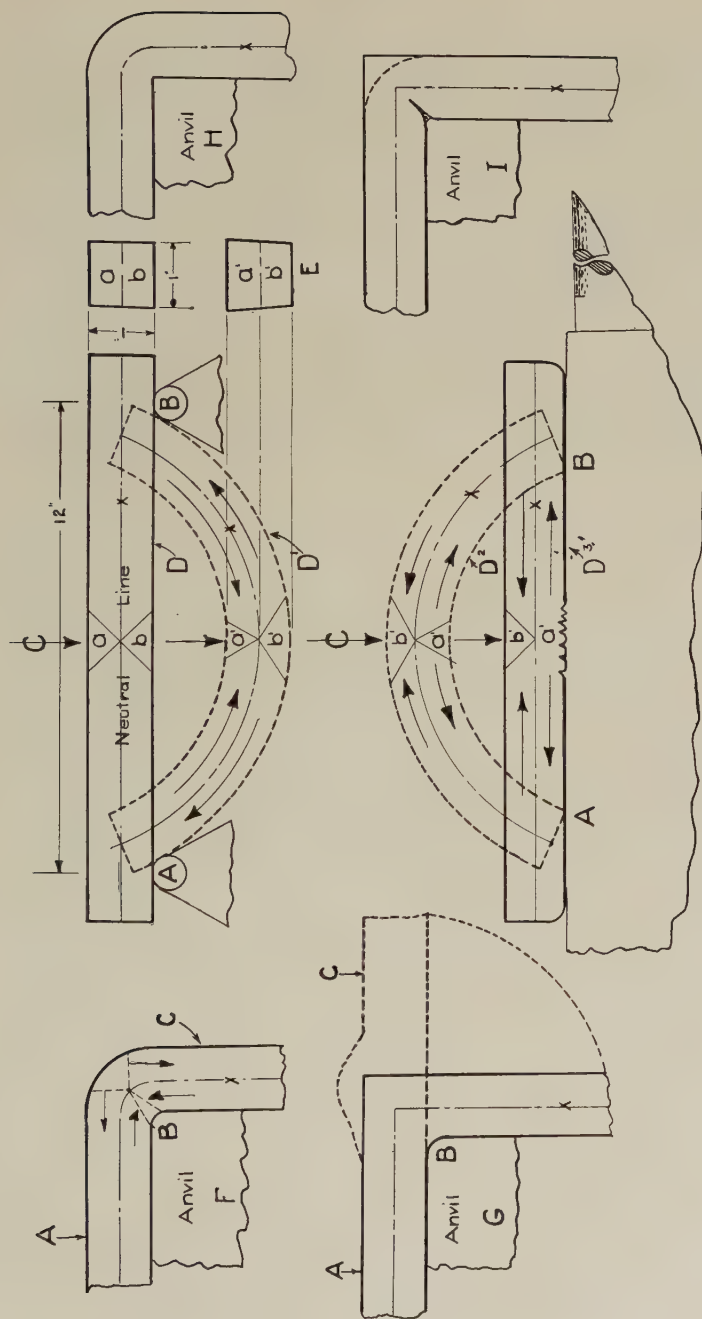


Fig. 57—Showing the Details of Bending a Bar of Iron.

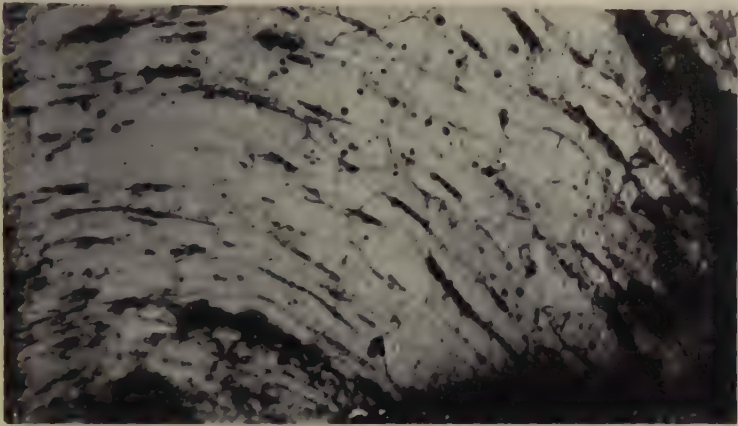
*Upsetting Machine*

The upsetting machine industry has kept pace with the times and eliminated many of the conditions as described. Particularly in the attempt to upset long sections, the makers have overcome this difficulty by redesigning, the addition of new methods, and increasing the size of the stock. The old method is represented at A, Fig. 56, and the later method at B.

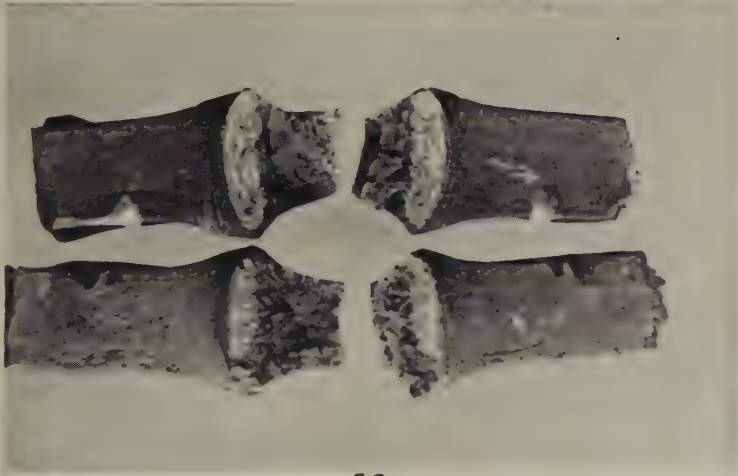
*Bending*

When a forging is drawn or upset to the cross section required, it may be necessary to bend it to the form of an angle or a ring. In order to bend or deflect a bar of metal from a straight line, it must be supported between two points with a load applied at a third point illustrated in C, Fig. 57. A bar of wrought iron (at room temperature) one inch square and 12 inches center to center of supports A and B will bend under a load C of about 2240 pounds per square inch. When sufficient force is applied to cause deflection from a straight line, a perfect radius may be formed in the bend as indicated at D<sup>1</sup> if the temperature throughout the bar is uniform. In cold bending the temperature of the metal is, of course, uniform. This is one of the reasons why iron and soft steel are bent cold when possible. When the metal is deflected from a straight line it does not change its original length unless pressure is applied to stretch or upset the stock in the bending operation. However, there is a movement of the metal on each side of the "neutral line" or axis marked "x". This line is always located in the center of the stock, indicated in D and D<sup>1</sup> at "x". It may be noticed that the angles "a" and "b" in the straight bar D, are equal. When bent, these angles have changed somewhat, as indicated, to "a<sup>1</sup>" and "b<sup>1</sup>" in D<sup>1</sup> and the angles are no longer equal. The metal on the inside of the axis "x" upsets while metal on the outside of "x" elongates or stretches. In uniformly annealed stock the movements of metal on either side of the neutral axis are about equal so "x" does not change its length. This is the reason that all calculations for bending are made from that line.

Let us study the effect of reverse movement upon the structure of the metal when bent in the cold state. Iron and steel are made up of an infinite number of minute grains joined together by



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Fig. 58. Showing Grain Structure of a Bent Bar of Wrought Iron.

Fig. 59. Photograph of Fracture of a Right Angle Piece of Steel That Broke in the Corner of the Angle. The Shiny White Surface and the Dark Portion of the Fracture Were in Alternate Tension and Compression. The Sharp Line at the Center of the Fracture is the Neutral Axis.

irregular cleavage planes. When bending takes place all of the grains on the outside of "x" are in tension and due to the ductility of the metal they elongate or stretch, the amount of stretch depending upon the ductility of the metal. If stretched too far, small cracks may be formed at "b" in D'. On the other hand all of the grains on the inside of the neutral line "x" are in

compression and such action may cause a slippage or separation along the boundry or the cleavage planes of the grains due to a slight horizontal movement caused from the upsetting of the stock, especially on the extreme edge of the metal indicated at "a<sup>1</sup>" in D<sup>1</sup>. At this point a very small overlap or cold-shut may form. Any grains distorted in cold bending, remain in their distorted state since metal at room temperature cannot flow of its own accord. Photomicrograph Fig. 58 illustrates the elongated grains of a bent piece of iron and Fig. 59 represents the two types of structure caused from a right angle bend. It also shows the neutral line or axis.

Let us now consider a reverse movement of this permanently distorted metal by examining the position of D<sup>2</sup> Fig. 57 and the possible result of straightening such a bent bar, D<sup>3</sup>. When a load is applied at C in D<sup>2</sup>, compression takes place on the outside of the line "x" and angle "b<sup>1</sup>". The distorted or flattened grains on the inside of axis "x" will be in tension. Repetition of this action may cause at least a minute crack. Therefore, alternating action may cause small cracks in that portion of the metal where the greatest distortion or deformation occurs, illustrated at "a<sup>1</sup>" in D<sup>3</sup>. This action may again be likened to that of breaking a piece of wire between the fingers.

A similar condition of tension and compression exists in the angle bend at F. Cracks will result if the bend is alternately straightened, then bent again. This figure also illustrates the advantage of bending metal over a round corner of an anvil or other bending device, so as to form a fillet on the inside of such an angle bend. An ideally reinforced angle bend is illustrated at B in G. Great care must be taken in the forging of a section of this character to prevent reverse movement of the metal accompanied by small cracks, especially when forging at low temperatures. One of the greatest dangers in the bending operation occurs in bending metal over sharp corners and especially over the corner of an anvil as illustrated at H. A bend of this character should never be allowed to pass inspection for a machine part or tool as the least reverse movement of the bent portion will cause sudden rupture at that point. For this reason all sharp corners should be eliminated from anvils, blocks and other bending devices as they are of no value in forging or forming operations except

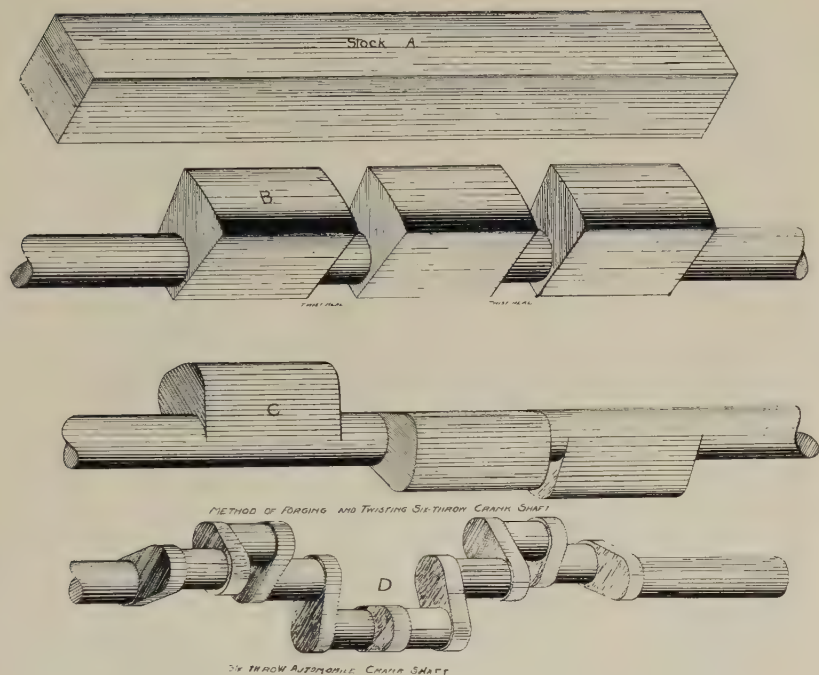


Fig. 60—Illustrating Steps in Forging a 6-Throw Automobile Crankshaft.

for that of shear or forming where sharp corners are unavoidable. Another serious defect is caused from attempting to reinforce the outside corner of an angle bend as illustrated in I. The continued movement of metal usually causes overlapping of the metal in the form of a cold-shut as indicated.

Let us note the effect of heat upon the strength and rigidity of the metal in the bending operation and also upon the grain structure. If the bar D is heated throughout to a soft white heat it will bend of its own weight when supported in the position indicated. Uniformity of temperature is very important in order to procure uniformity in the bending operation. If iron or steel is bent at a temperature slightly above the critical range and such bending is completed before crystallization ceases as indicated in Fig. 35, the grains will adjust themselves due to their mobility. This adjustment continues until the lowest point of the critical range is reached. If continued bending takes place below the  $A_1$  critical temperature, we may strain and elongate the grains as

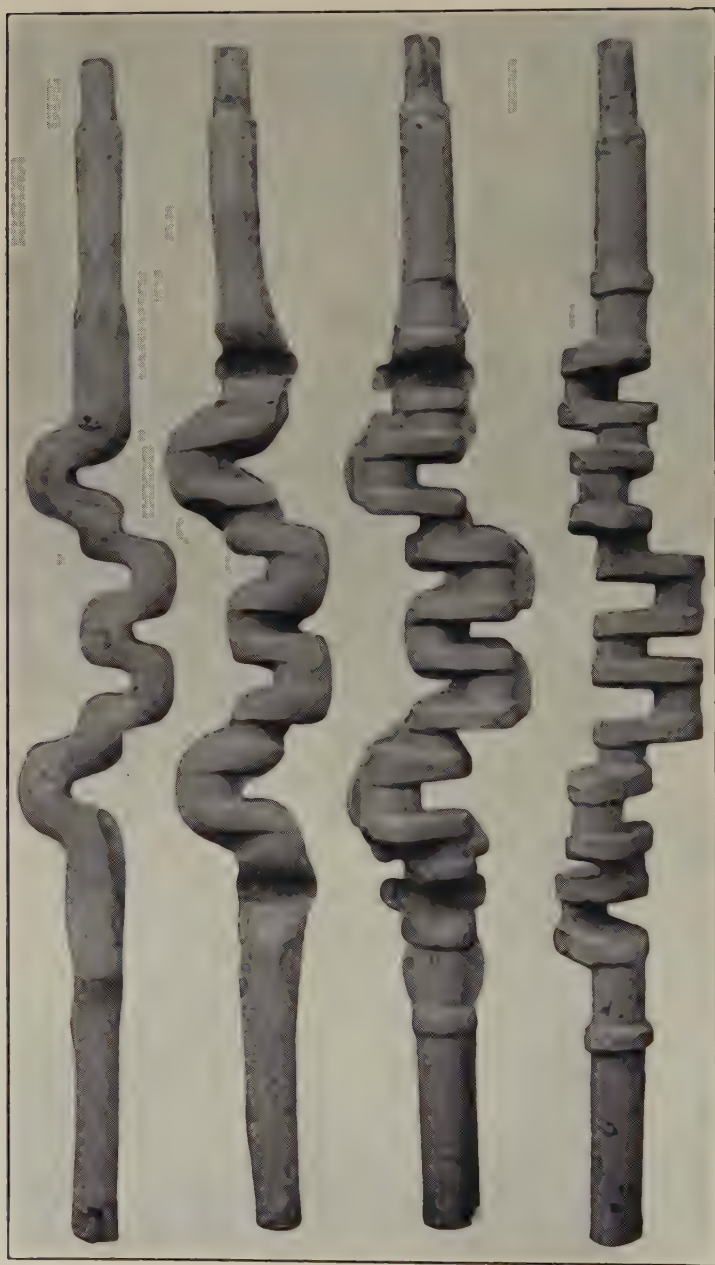


Fig. 61—A 6-Throw Crankshaft Forged with Cranks in Proper Alignment During Forging. No Twisting Was Necessary for this Alignment.

described under cold bending, due to the fact that there is no mobility of the grains below that temperature. Annealing just below the critical range will relieve all strains from such cold working and impart a uniform grain structure, but it will not unite any ruptures.

### *Twisting*

Twisting operations are used for many purposes, particularly in ornamentation and proper alignment of parts. The automobile crankshaft is a good illustration of this principle, and is used quite extensively in the proper alignment of such parts, even today. In the early development of the automobile, the writer had some experience along this particular line. Fig. 60 illustrates the

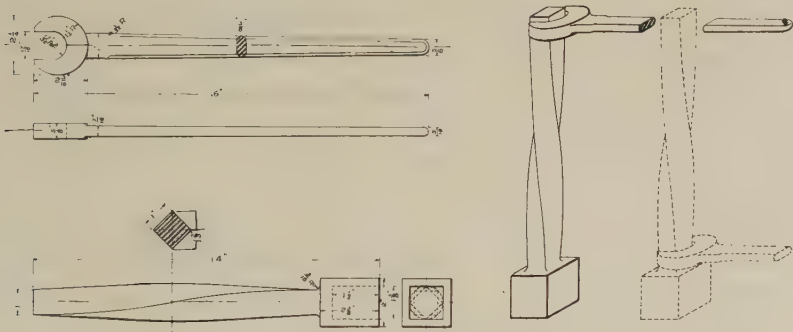


Fig. 62—Design for a Twisted Socket Wrench.

crude method of manufacturing a six-throw crankshaft in those days. At the time this shaft was ordered a similar shaft was made in Paris. The Paris firm used a cylindrical section  $6\frac{1}{2}$  inches in diameter and removed 262 pounds of surplus stock. The writer made the shaft as indicated at D out of stock  $3\frac{3}{4}$  inches square, indicated at A. Both ends of the shaft were drawn as at B and the cranks proper were tapered as indicated, then planed, heated and twisted as indicated at C. Considerable surplus metal had to be cut out from each of the sections at C in order to complete the finished shaft as indicated at D. Incidentally this shaft was made out of cold-rolled stock and was finished and put in service without even simple annealing, normalizing or any form of heat treating to impart better physical characteristics.

Today the crankshaft may be formed to shape under the drop

hammer and made in one plane, then heated and cranks twisted to their relative positions. Finally the shaft is annealed, normalized, probably time-quenched and tempered (drawn) to impart the desired physical characteristics.

The greatest achievement in this line of work took place during the war. A hammer die was designed to complete the Liberty motor crankshaft and properly align the cranks without twisting when it left the drop forge die, Fig. 61. Today this method of forging crankshafts is in general use.

### *Twisted Socket Wrench*

The old saying, "Necessity is the mother of invention" holds true in the case of the design of Fig. 62—a twisted socket wrench. It was designed to loosen a nut that was impossible to reach with any other type of wrench. Such a wrench has proved very convenient in close places. This design is suggested over wrenches that have numerous holes at various angles requiring a special bar for twisting. It requires a square piece of soft steel containing about 0.30 to 0.40 per cent carbon, welded on to the socket wrench. In the heating and twisting care must be taken that the bar is uniformly heated throughout its full length, then it is twisted one-quarter turn.

This and parts for power transmission should always be twisted at uniform temperature somewhat above the critical range. This will impart a uniform twist with less power in the operation and without the least danger of shearing the metal axially. If such an operation is finished before any portion of the metal has reached the lowest point of the critical range the grains will continue to adjust themselves, leaving no strains in the metal. On the other hand if twisting takes place below the critical range the structure will be more or less strained. Proper annealing will remove this strained condition but will not rectify any permanent rupture that may occur from twisting below the critical range or in the cold state. However, much of our wrought iron, soft commercial steel and many heat-treated parts may be twisted when cold without much danger, depending of course upon the ductility of the material. Twisting is also a good criterion of the quality of the metal and is used as a test to determine its ductile characteristics.

## BLACKSMITH WELDS

Blacksmith-welded parts in engineering practice and in our highly efficient parts of machinery for power transmission are not as a rule advised or recommended where human life is involved or where serious failures would be disastrous. It is humanly impossible to make this type of weld 100 per cent efficient unless the cross section is increased in order to develop additional strength.

The writer after many years as a practical welder, in 1907 had courage enough (or was it ignorance) to say that a welded part never failed in the weld. Some of the listeners requested "facts" for that statement. Physical tests of the writer's product soon removed his ignorance. Then he began to investigate the many factors that might possibly affect the production of an

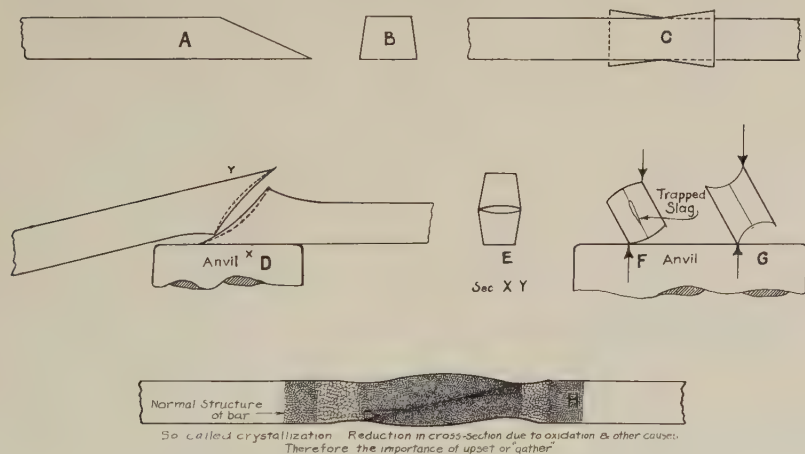


Fig. 63—Illustrating Some of the Principal Causes of Defects in Welds.

efficient weld. A few of the factors affecting a weld are as follows:—

1. The weldability of the material
2. The fuel and impurities detrimental to welding such as sulphur, phosphorus, ash, etc.
3. Type of heating unit, forge or furnace
4. Atmospheric condition of fire or furnace
5. Scale (oxide of iron) dirt, ash, etc.
6. Flux—its application and abuse
7. Uniformity of temperature of the two pieces
8. Grain growth

9. Dissimilarity of metal in welded parts
10. Burning
11. Carburizing of welded parts in contact with fuel of fire or furnace
12. Decarburizing of welded parts due to excess air or free oxygen
13. Microscopic rupture due to expansion or contraction upon localized heating or cooling
14. Ability of the welder
15. Mechanical working of welded parts
16. Unequal cross section

### *Defects in Smith Welding*

The disadvantage of no "gather" or upset and the long wedge scarf spread out at the point are indicated at A and B, Fig. 63. When two such pieces as A are heated to a welding heat, the section of A just behind the scarf must reduce in cross section due to surface oxidation illustrated in H. If the two points come in contact with the fuel of the forge, the surface of the scarf becomes carburized. If the wide butterfly scarfs as at B are not burned off (which they usually are not) and both pieces are at a welding temperature they are then placed as in the position of C.

The force necessary to unite the material is applied on top of the bars, at C and then the piece is turned upside down to weld the section together. This operation further spreads the entire weld, including the points of the scarf, in a horizontal direction. The next effort of the smith is to weld the points of the scarfs as indicated by the arrows at G. From the information on the drawing of metal between flat dies, one may imagine what takes place here, if an excess force is applied. The next common fault is to first "gather" or upset sufficient stock to allow for wastage, etc., but in scarfing the points, the scarf is usually spread too wide, making a condition similar to that shown at C. If the scarf is too wide the points are sometimes closed in, forming a cup scarf indicated at D, and the exaggerated cross section at E. This and similar types of scarfs trap scale, dirt, ash, etc., on the surface of the scarf, which cannot escape, thus preventing complete welding of the metal. This is shown at F.

One might write a number of pages reciting many other causes but those described should show the reader the reason for the lack of 100 per cent efficiency in such welds. The reader will conclude that the writer is somewhat pessimistic on this phase of the subject, and to be frank, he is. The following may help to a better understanding for this state of mind. In the construction

of an experimental automobile about 1903, the front axle was forged out of cold-rolled metal. Picture the axle having a jaw on each end for reception of the front wheel spindle. When nearly finished it required some slight alignment, and was struck a blow with a sledge in the center of the axle between the jaws. The vibration caused by the blow was so great that one of the jaws broke off. The engineer in charge decided to repair the axle by split welding on a new jaw. When welded properly, it was bent over at right angles to form the top part of the jaw, finished over at right angles to form the top part of the jaw, finished

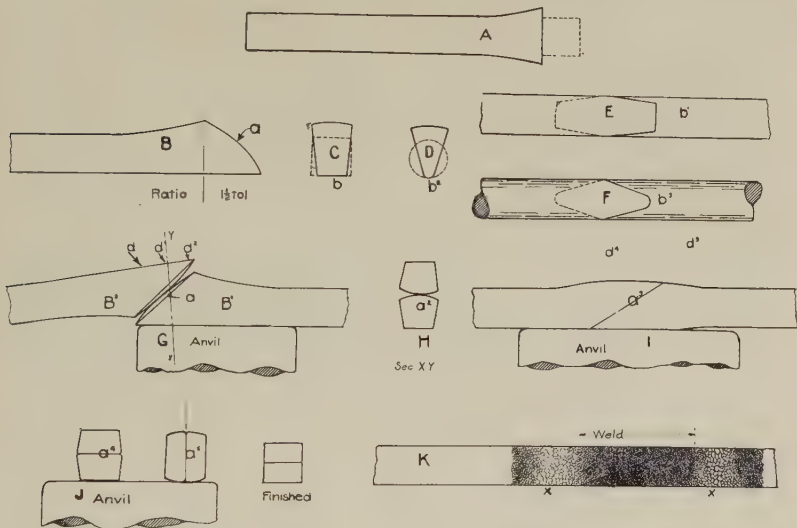


Fig. 64—Illustrating Some of the Principles of Making a Scarf Weld.

and was put into service without even a simple anneal to remove stress.

The writer had the pleasure of riding in that car at the terrific speed in those days, of 40 miles per hour. That was one case at least, where "ignorance was bliss." With our present knowledge of steel it would be a criminal offense to even suggest such material in any parts of tools or machinery, especially where a life might be in danger.

For those desiring to learn how a better smith weld may be made, the writer offers the following suggestion, outlined in Fig. 64. When the metal is heated to a welding temperature it is

usually reduced in cross section due to oxidation (burning). The metal is also reduced in cross section by the welding operation. It is essential to "gather" or upset a sufficient amount of metal in the direction in which it receives the most intense heat, and to hammer a great deal in the welding operation and in reducing the piece to normal dimensions.

A indicates "gathering" the end of the stock by upsetting, while B illustrates a form of scarf that will meet all the requirements and objections previously explained. It also indicates the ratio of the length of scarf to the cross sectional area, with the center of the scarf point "a" rounded or convexed as required for a successful weld. C is a cross section of figure B and shows the regulation point of the scarf for square or rectangle sections, while "b<sup>2</sup>" in D indicates the proper point of scarf for round sections. The advantage of the narrow point "b" at C is indicated at E b' for square, rectangular and flat stock, while F b<sup>3</sup> indicates the narrow point for round stock. It may be noticed that when a blow of the hammer is delivered on points indicated in E the stock should unite with the piece underneath and also spread to the full dimension of the square or rectangular bar at hand. The point F b<sup>3</sup> should unite with the round stock in one or two blows of the hammer.

When both scarfs are made in the form of B and heated to a uniform welding temperature, B<sup>1</sup> should be placed on the edge of the anvil indicated in G with the point of the scarf projecting over the edge as represented. The object of placing the scarf in this position is to prevent the cold anvil G from cooling the point of the scarf, which would happen if placed in contact with the face of the cold anvil. The piece B<sup>2</sup> should be placed in the position indicated so that the point is in contact somewhat above the center of the scarf indicated in G. The object of placing it in this position is to allow for slippage, if the blow of the hammer be delivered perpendicularly to the face of the scarf as indicated by the direction of the arrow "d". This operation will cause the centers of the pieces to stick together (if prepared properly and at a welding heat) and also force out any slag that may be on the surface. A cross section of the point "a" in B<sup>1</sup> is indicated at H a<sup>2</sup> where it may be noted that there is opportunity for such slag, dirt or flux to escape. If a series of blows is delivered as in-

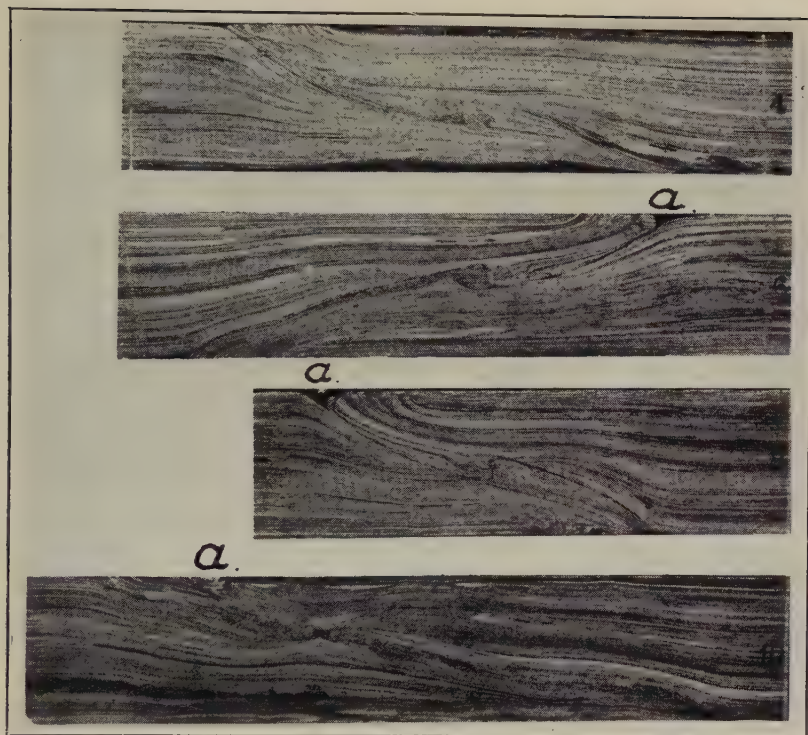


Fig. 65—Scarf Welds Etched to Show Lines of Metal Flow and Contact Surfaces of the Weld.

dicated in G by the arrow “d”, “d<sup>1</sup>” and “d<sup>2</sup>”, that portion will be welded, then by turning it 180 degrees or upside down, moving it forward on the anvil and repeating blows “d”, “d<sup>1</sup>” and “d<sup>2</sup>”, the pieces should be welded together except for the edges of the scarfs indicated at I a<sup>3</sup> and J a<sup>4</sup>.

If the weld is then turned 90 degrees or a quarter of a turn it will place the line of contact between the two plates perpendicular to the face of the anvil indicated in J a<sup>5</sup>, when welding of the edges may take place and the stock can be reduced in cross section by upsetting without a slip or shear effect taking place in the weld. It would be well to keep in mind at this stage of the operation that no further welding takes place between the pieces (except the edges which may be closed or drawn over one another) when the points of contact between the plates are perpendicular



Fig. 66—Showing the Grain Size of Steel Under Various Conditions.

to the force of the hammer, previously illustrated and explained in the drawing of a square section, Fig. 36.

Perfect welding can only take place when the line of contact between the pieces is at right angles to the force of the hammer. If this operation is continued until the cross section is reduced to its original dimensions, no defects will be caused from the operation, provided that all necessary points of scarf, etc., are thoroughly united at a welding temperature. This operation should be adhered to in the welding of rough sections even to that of finishing the pieces by swaging, except in welding down the corner when a light blow should be used so as not to disturb the line of weakness by shear between the welded plates. Continued hammering in the proper direction of an apparently perfect weld until the temperature has dropped to a dark red heat has its advantage in compressing that portion under the hammer and closing of all voids between the joints. It also prevents the development of large grains as shown in Fig. 37.

The granular structure of such a weld is illustrated in K, Fig. 64 (etched to show flow lines). The grains at the welded portion appear very small. This condition is due to continued working of the welded parts until the temperature has lowered to a dark red heat or to the  $Ar_1$  point. If working be continued until the metal has been cooled below the lowest point of the critical range,  $Ar_1$ , the structure will be in its finest possible state. Hammering below the critical range, will only distort the structure by stretching or elongating the grains, which action causes external and internal strains. A structure distorted by cold working, i.e., below the critical range, means decreased ductility and eventually extreme brittleness. Welded parts should never be hammered at low temperature owing to the above and the possibility of disturbing the cohesion between the welded parts.

The strength and general efficiency of material is proportional to the fineness of grains; therefore, the weld that has been hammered properly should be strong and efficient, provided that it is thoroughly united together. While this condition of a perfect weld appears possible to the eye, it is stated that, by welding, "a joint may be made which cannot be seen with the eye unless the steel is polished and etched with acid which usually develops the junction line very clearly", indicated in Fig. 65.

Such a weld hardly ever fails directly in the welded part, but it usually fails adjacent to the weld and from one of two causes. First, a small defect at the extreme points of the scarf "a", Fig. 65 may cause failure due to a reduction in its cross section. Secondly, metal adjacent to the scarf which has not been upset or "gathered" sufficiently in usually heated to a white heat which requires some time and results in grain growth. The heating of the larger pieces requires a considerable length of time and the temperature is usually in the granulation zone, above the  $A_3$ . This condition of high temperature develops large crystals which are not prevented from further growth by work until the undisturbed metal cools to the  $Ar_1$  point. This condition of grain growth from high temperature, is indicated in K, points "x x", Fig. 64. Heat treatment properly applied should impart uniformity of structure and relieve all internal and external stresses. This statement should be applied to all fabricated material heat treated or ill treated as above described.

## GRAIN GROWTH OF FORGED PARTS

The term "crystallization" as often used in the industry is illustrated by the fractured samples in Fig. 66. As previously stated, this condition of large grains is due to heating at too high a forging temperature, very little working of the metal, or to improper heat treatment. The condition of grains within the metal often is given very little consideration by hammermen. Often, their object is to forge or weld the parts together and to form the shape desired with the least amount of energy and cost. Fig. 66, A shows various fractures of wrought iron. B shows fractures of a 0.30 per cent carbon steel. D shows fractures of tool steel, E shows high speed steel, and F is a malleable iron casting before annealing. In each set, the bar showing fine-grained structure is evidence of proper heat treatment. The coarse-grained structures indicate heating at too high a temperature.

One author writes as follows:

"From our investigation of the various metallurgical texts we are unable to find any reliable proof offered that vibration had caused or is capable of causing large crystals in iron or steel. It may be possible, but the more we learn about the subject the more we are inclined to believe that insufficient amount of work and improper heat treatment is the cause, and that the crystals were large before the steel was put into service, although its nature was not disclosed until the break occurred."

A machine operator making 1-inch bolts on a bolt header used an oil furnace for heating. The furnace held about 30 pieces of material. An accident occurred to his machine which required about twenty minutes to make repairs and he did not shut down his furnace in the meantime. The writer asked him why and he said that he was working piece work and wanted to keep the rods hot so he could proceed when the machine was repaired. When one of those bolts failed under the head what would be the cause of the coarse grain or crystalline structure?

This sometimes occurs in all lines of forge work, more especially in machine forging. The machines are designed to form a forging at one heat and in one or two blows or revolutions of the machine, where it formerly required a number of blows or passes, or perhaps hours on the anvil. In order to attain the proper re-

sults the metal must be heated to a soft white heat and in many cases to a welding temperature. There are three reasons for such a high temperature: First, to weld the parts; secondly, that the metal can flow freely and fill all impressions in the dies; and thirdly, that the power required be reduced to a minimum. It is not at all unusual to see a number of finished forgings thrown on

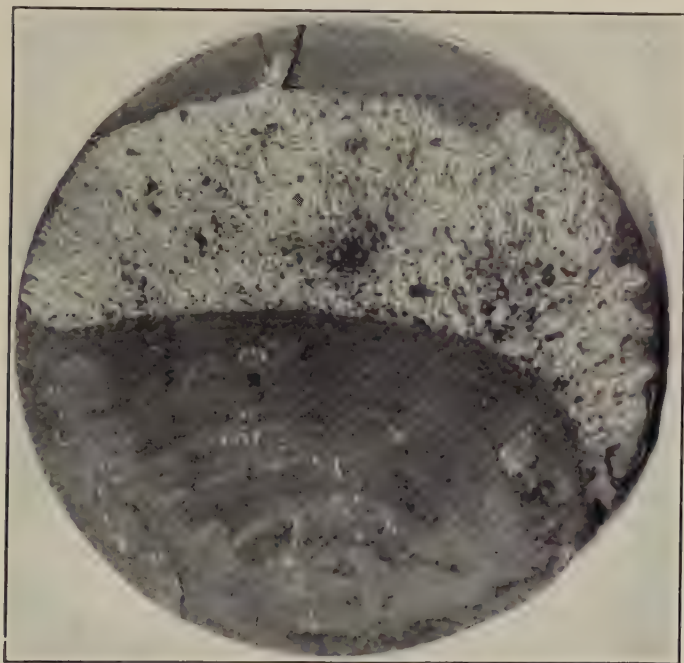


Fig. 67—Showing a Hammer Piston Shaft That Failed by Fatigue.

a pile when at a very high temperature, while similar forgings may be hammered until they are black. This occurs in forgings that cannot be finished on one heat. These two extremes are not conducive to equality in the parts so treated. Therefore, in order to impart a uniform structure it is necessary at least to give such parts a simple annealing. It is the opinion of some men that all that is necessary is to heat to a high temperature and cool slowly.

The following incidents will illustrate some of the practices followed in non-procedure controlled industrial plants. A crane chain conveying a large ladle of molten metal failed, injuring sev-

eral workmen. Upon examination of the fracture it was found to be coarse-grained. The engineer in charge suggested that it be annealed and the annealing was performed in the following manner.

The chain was piled in a cold oil burning furnace at about 4:30 p.m. The furnace was heated quickly as the men quit at 5:30 p.m. In a short time the top of the pile of chain in direct path of the flame became white hot. At quitting time the operator shut off the fuel supply, sealing the furnace and made this statement: "The chain will be uniformly heated and thoroughly annealed by tomorrow morning." Upon examination of the alleged annealed chain next day, it was evident from the appearance of the scale that part of that chain never reached a red heat, while other parts had attained a temperature far beyond that required. How could such treatment produce a uniform structure in the metal?

#### FAILURE OF STEEL BY FATIGUE

When steel parts break, the statement is often made that the part "crystallized", implying that vibration or some unusual condition caused the grains in the part to grow so large that they could not withstand the loads applied and so the part failed. In reality, the part "failed from fatigue" and this class of failures is usually discussed under the heading "fatigue of metals."

Fatigue of metal is due to repeated reversal of stress, as in an automobile axle shaft. In making one revolution, a certain spot will alternately be in tension, and then compression. A small crack at this point would be alternately opened and closed. Such cracks often start at the sharp corner of a part such as a square shoulder, sharp corner, or even a tool mark. Alternate bending, first in one direction, then in the other will gradually open the crack, even if the movement be ever so slight. The path of the crack or fracture is from grain to grain, either across or around each grain. The fracture looks very jagged, having the appearance of a collection of large crystals, hence the notion that the metal has actually crystallized in service and that the grains have grown larger and larger.

Fig. 67 shows a fatigue failure in a small hammer piston shaft. The smooth surface above and below the coarse structure at the center is the result of the butting or rubbing together of these

faces every time the shaft was in compression. It is evidence that the shaft did not break suddenly, and that the crack progressed little by little. As the crack progressed, the metal intact grew less and less. The remaining metal broke suddenly as the load was then more than it could support. Probably a sudden shock finally caused rupture.

Illinois University and many industrial concerns have spent considerable time and much money in studying the fatigue of metals. They have found that internal defects such as pipes, blow holes, and slag or other inclusions often form the root of a fatigue failure. Sharp corners are probably the most frequent cause, and these investigators advise against the use of sharp corners in rotating parts whenever possible. Cracks caused in rolling and forging operations are very often the source of fatigue failures.

#### PURCHASING AND INSPECTION

##### *Selection of Steels*

In procedure controlled plants, the material is usually purchased under chemical or physical specifications outlined by government experts, committees from the various technical societies and others. Such specifications and outlined treatments for each specific type or kind of material are available at the various societies. Many of the steel and supply companies furnish copies gratis.

When material is purchased for plants having metallurgical advisors the raw product is checked by chemical analysis and inspection, but when we consider that not 10 per cent of the metal trade plants of the country have metallurgical control, what check or system of buying do they adopt? To such concerns the writer would advise doing business with reputable firms, and taking advantage of their highly trained metallurgical advisors and well-equipped chemical and physical laboratories. In other words, submit your problems and be governed by their advice.

When we consider the initial cost of raw quality steel; it is insignificant in comparison to labor cost of the finished product. Quality steel fabricated with skill and care will in turn make satisfied customers. On the other hand, the cost of producing tools, etc., from an inferior steel is about the same as for a quality steel

but the result is usually a poor part or tool and probably a lost customer. The writer believes in being absolutely sure of the company with which one deals. Transact business with their authorized representatives and avoid the supersalesman who offers something for a price. By following this practice one will reduce and probably eliminate trouble and grief in the plant.

### *Storage and Identification*

Upon receipt of raw material great care should be taken to see that each grade, kind or quantity of steel is correctly marked for future identification. Experience has proven conclusively that carelessness in the storage shed creates untold trouble and grief in the plant. It is a simple matter to pick out and separate human beings because no two people look alike, but bars of steel of similar size and shape have none of the surface characteristics that distinguish the average human being. Identification marking is an absolute necessity. This point should be strongly emphasized to those having charge of incoming material, its storage care and distribution.

### *Marking for Identification*

There are many methods of identification, too numerous to mention here, except those of different colors and combinations of color paints. It often appears that an official taking charge of a plant has his own idea of how steel should be marked.

One experience of the writer will illustrate this condition. Picture in your mind a plant about 60 years in business which changed hands numerous times. During that period each of the new officials painted the old steel stock different colors. Then picture the tool room employing about 100 men, in which the tool and other steel stock was stored in a partitioned-off section of the room without a storekeeper. All material was marked for identification (painted) and the men selected it according to the color paint combination. Customers' complaints of mixed steel required some investigation and the writer was assigned the task. Invoices showed about 10 tons of all kinds of steel and bars of various sizes, shapes and lengths. Chemical analysis was out of the question, therefore it was necessary to resort to the spark method. Under one distinct combination of color paints 2500



CROSS BARS EVERY THREE FEET OR LESS

Streak Bars	Red High Speed	Yellow Tool Steel	Green Mach. Steel	Black Finished Steel	Blue Nickel Steel	White Special Steel	No Mark Screw Stock
Blue	Blue Chip	0.80 Carbon	0.15 Carbon	0.15-0.25 C	3.50 Ni	Low Ni, Cr	
White	Novo	0.90 Carbon	0.25 Carbon	Turned—Gr 0.25-0.35 C	0.15 C	0.30 C, Ni Cr	
Yellow	Rex AA	1.00 Carbon	0.35 Carbon	Turned—Gr 0.35-0.45 C		0.45 C, Ni Cr	
Green	Columbia	1.10 Carbon	0.45 Carbon	Turned—Gr		0.15 C, Cr V	
Black	Colonial	1.20 Carbon				0.45 C, Cr V	
Red	Red Cut Superior	Non-shrinking		Drill Rod	3.50 Ni 0.45 C		

Fig. 68—Suggested Method of Marking Steel for Storage.

pounds were listed as high speed steel, at least the invoice of sale so recorded. After very careful testing against samples of known steels, we found seven distinct grades of material and only 18 pounds of high speed, originally invoiced at 2500 pounds.

With this experience in mind, the writer is offering the method of marking steels for identification shown in Fig. 68. If some reliable system of identification is used throughout the entire process of manufacture, even that of a single tool, the system will more than compensate by the elimination of many shop troubles.

### *Methods of Selecting Steels for Parts and Tools*

From observation, it has been found that the various methods of selecting steels for any given purpose form a serious and costly problem—serious; first, because of the many injuries to workmen and others, due to failures of parts and tools made from material unsuited to the work for which they were required; secondly, because of the failure of important parts in service. Many failures can be traced to the selection of materials which were inadequate for the requirements of such parts.

The scrap piles of commercial plants furnish many excellent illustrations of this point. In most cases, the wasted material amounts to comparatively little in comparison to the money lost in labor spent on it. This waste cannot be entirely eliminated because as long as man does a great amount of work or experimenting, there will always be mistakes and "scrap". By educating men in the basic principles of the material they deal with and adopting a system of procedure control the scrap pile will be reduced.

In plants not under procedure control, selection of material is usually made by at least one of the following means:

- (1) Using convenient odds and ends without reference to analysis or physical properties of the material,
- (2) Prescribing steel that has proven satisfactory from experience,
- (3) By a service test—checking experience by testing the part under actual service in the field,
- (4) By following recommendations of an engineering handbook, and
- (5) By following the steel company's recommendation.

The last three methods are to be preferred. Once a type of steel is established and proven for a given job, it is best to continu-

ally purchase steel from the same mill especially in non-procedure controlled plants. Reputable steel mills do everything they can to always deliver the same quality of product made under a certain brand name.

Procedure controlled plants usually specify chemical analyses and physical standards for all materials. These specifications are written by men of long experience and when set, they are rarely changed. Engineering handbooks and standards established by various technical societies are often used in writing these specifications. Steel bought to widely used specifications is lower priced than steel of special specification that must be melted and rolled in special heats as a special order. Incoming shipments of material are checked by the chemical and physical laboratory to make sure that it is according to specification.

Now let us sum up a few of the methods used in storing and selecting steel for some specific purpose.

(1) *Mill methods of identification*: (a) paint; (b) stencil marks; (c) labels pasted on bars. These are all dependable in dealing with reputable firms but in the case (c), if bars are piled in moist places the labels may drop off.

(2) *Shop method of painting different colors*. This method is reliable only when properly applied by responsible employees.

(3) *General shape of material* is no criterion of quality because all plastic metal may be rolled or forged into shape.

(4) *Appearance of the surface*. To select metal by this process would be foolish in the extreme for surface finish or unfinish is a matter of how much or how little work was applied upon the surface. Cold-rolled steel and drill rods are splendid examples of this fact.

(5) *"Heft" or weight of the metal*. There is a slight difference, carbon steel weighs about 2 per cent heavier than iron while high speed steel weighs about 11 per cent more than carbon steel. Selection by this method is pure guess work.

(6) *Ring or tone of metal when dropped*. Iron usually has a low or dull tone due to slag inclusions, and steel, a sharper tone. Selection might be made between these two metals but then it would be questionable. The writer has demonstrated the possibility of developing six tones on the same size, length, and type of steel by various processes of heat treating.

(7) *Feeling, ability to determine by touch and intuition.* It simply cannot be done.

(8) *Fracture test.* Much may be learned from a study of the fractures of different steels. This test is not reliable unless one has a knowledge of the material, the treatments it may have undergone, etc.

(9) *Heating and quenching test.* This test is only of value in determining if the metal under test will harden and refine properly. Cut a disk from the end of the bar about  $\frac{1}{2}$  inch thick, heat it to a dark red heat, quench it quickly in cold water and test all surfaces with a good sharp file. Clamp one end of the bar in a vise and break it into two pieces. If the fracture shows a fine silky grain and is hard clear through, one may be sure that he has a piece of steel that will at least harden, and might be used for tool purposes. At least, this test will eliminate making tools out of soft material.

(10) *Service test.* Many workmen and some experimental engineers select available material without much serious thought of its quality, then put expensive labor upon the part or tool. When finished, it is tried out in service. If it fails, something else is tried. Such failures are usually found in the scrap heap. Why not procure information first, select a steel knowing what it can do, and save the risk of scrapping an expensive finished tool or part? The service test has its advantages, especially to the engineer, provided that he keeps a record of the material so tested. He usually bases his selection on engineering data and uses the service test to check his selection. The experimental engineer, in considering the choice of steels for many purposes, has before him the well kept record of previous service tests. This information is invaluable as it is the combination of successes and failures that gives the empirical knowledge which completes the perfect understanding of theory. A record of the life work of a piece of steel and accurate data are the most useful tools that an engineer has to work with. Therefore, the scrap heap of failures is a most instructive place about a plant in more ways than one. Knowledge gained there by an observing engineer or metallurgist may be used to advantage.

(11) *Spark Test.* The spark method is in general use for preliminary tests, but even then it is not absolutely reliable. How-

ever, if applied intelligently, it will come closer to determining certain steels, than many of the crude methods above described.

### *Checking Incoming Material*

Chemical analysis is the only infallible means of determining chemical content. The "spark method" can be used to advantage as a check on each bar, each bundle of wire, or a test lug from each billet. But the chemical analysis alone does not tell the whole

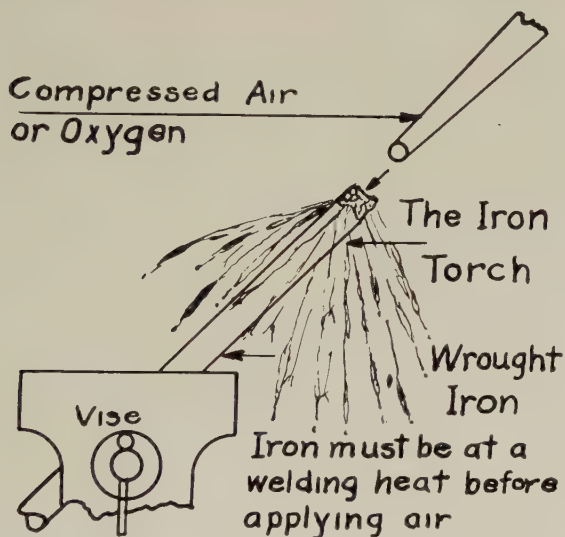


Fig. 69—Demonstrating the Burning of Iron, "The Iron Torch."

story. Steel made to the same analysis even by the same method may show considerable variation in physical characteristics. It is therefore best to select samples of incoming stock and check them under the microscope and in the physical testing laboratory, in addition to checking the chemical analyses.

When a quantity of steel is furnished from the same heat the product should be quite uniform; therefore, the chemist's problem would be to analyze a few bars selected at random, but if the material was from mixed heats, then in order to arrive at an accurate conclusion the chemist must analyze each bar. In much government work this is a requirement, regardless of mill analysis. This would require considerable time and expense even where a metal-

lurgical chemist is employed at the plant. The Brinell, scleroscope or Rockwell hardness tests are used to some extent in testing material as received from the mill. Heat treatment and changes in the physical characteristics of steel, can be gaged fairly well, but it is questionable if hardness testing is an accurate gage of chemical



Fig. 70—Meteorite Brought from Greenland by Admiral Peary in 1897.

composition. Microscopic examination is not thoroughly satisfactory in determining the chemical composition of metals and especially alloy steels, but is very reliable in determining the heat treatment and therefore physical properties.

#### SPARK METHOD OF IDENTIFYING IRON AND STEEL

The spark method is based on the action of the oxygen of the air upon the combustible elements present in iron. To produce bright sparks as the result of heating finely divided particles of metal, the heat must be intense enough to cause chemical combustion between the oxygen of the air and the particles of metal. We have many noticeable demonstrations of this fact, such as the

sparks thrown from between locomotive driving wheels and the rail; the grinding of street car rails in your city; and the beautiful pyrotechnic displays at important celebrations.

Iron will burn quickly under certain conditions. A demonstration of this fact is represented in Fig. 69. By heating the end of a bar of wrought iron to a melting heat and holding the



Fig. 71—Illustrating the Effect of Too Heavy a Pressure on a Tool Against an Emery Wheel.

melting portion under a stream of compressed air it will at once begin to burn and scintillate, (very dangerous to observers at close range without colored glasses). By maintaining the stream of air the iron will burn or melt for an indefinite period. This demonstration is of educational value for it represents the Bessemer process of making steel and it demonstrates the real cause

for burning iron and steel in the forge fire or furnace. The straight line sparks are further evidence of combustion. When a portion of the rod has been burned, shut the air off until the metal cools below a melting temperature, again apply the air and note how very rapidly the hot iron scales (oxidizes).

Apply a neutral flame from an oxyacetylene torch until the end of the bar attains a welding heat, then shut off all acetylene gas and apply only pure oxygen to the heated end. If at the correct temperature this iron torch will burn for hours without any source of heat, except that caused by the combustion of iron in the excess of free oxygen. Another example may be obtained by

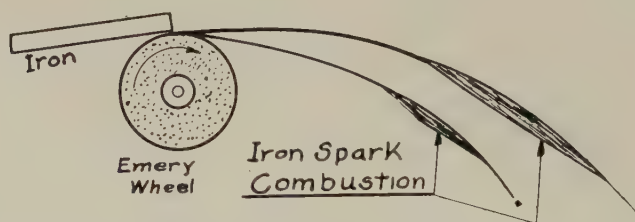


Fig. 72—Illustrating the Application of a Tool to an Emery Wheel in Making a Spark Test.

dropping finely divided particles of iron or steel into a fire say a Bunsen burner, or gas flame. The flame is not hot enough to melt the iron, but the heat is sufficient to cause combustion of the heated iron and the oxygen of the air, giving off bright sparks.

Meteorites travel at high velocity in our atmosphere. The frictional resistance of the atmosphere heats the mass. This heat plus contact with free oxygen causes combustion to take place on the surface of the meteorite and accounts for the broad tail of sparks that follow a comet or shooting star. The largest and heaviest meteorite known weighs more than 36.5 tons. It was brought from Melville Bay near Cape York, Greenland, by Admiral Peary in 1897 and is on exhibition in the American Museum of Natural History. The following are its dimensions and chemical composition:

<i>Dimensions</i>		<i>Composition</i>	
Length	10 ft. 11 in.	Iron	91.48%
Thickness	5 ft. 2 in.	Nickel	7.79%
Height	6 ft. 9 in.	Cobalt	0.53%

A reproduction of the above is shown in Fig. 70. Note the size in comparison to the guard's hat.

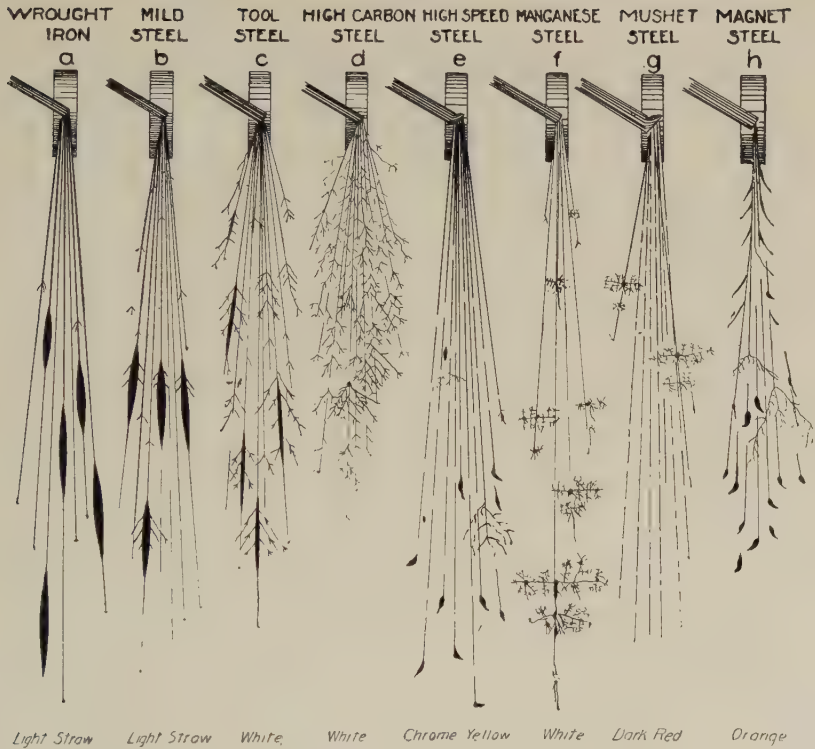


Fig. 73—Characteristic Sparks of Various Irons and Steels.

If a piece of iron or steel is pressed against a high speed revolving emery wheel a large quantity of sparks is thrown in all directions, the result of combustion identical with the examples just given. If the pressure is too heavy, the sparks will travel completely around the wheel as indicated in Fig. 71. The pressure should be just sufficient to produce a few sparks, and no more as shown in Fig. 72. The ideal would be to touch a piece of metal in such a manner that it would throw one or two sparks then it would be a simple matter to note the spark characteristics.

Much time and money have been spent in attempting to photograph the sparks from different steels but we have been unable to secure anything worth while; therefore, we have resorted to the pen drawing, Fig. 73, in order to furnish a pictorial illustration of the sparks from different steels. While the different sparks as

drawn are not absolutely correct, they will give a fair idea of what to look for.

There are a few precautions necessary for this test; (1) a clean cutting emery wheel revolving at a peripheral speed of 6500 to 7000 feet per minute; and (2) just enough pressure on the wheel to throw only a few sparks. Referring to "a" Fig. 73, if a piece of wrought iron free from carbon is held against a high speed revolving emery wheel sparks will be emitted. As the small heated particles are thrown from the wheel they follow straight lines which becomes broader and more luminous some distance from the source of heat. If the particles are not all consumed, they fall to the floor similar to the action of the meteorite or shooting star. The distance of the broadening of the streak of light is probably due to the oxygen of the air requiring some time to act. All commercial iron contains a small percentage of carbon as indicated by the slight branching or forking of the luminous streak, shown at "b". If we touch a piece of mild steel (cold-rolled) containing a small percentage of carbon, the effect is at once noted by a division or forking of the luminous streak as at "b". With increase of carbon (tool steel) the iron spark lines diminish, becoming less conspicuous. As the carbon increases, the forking of the luminous streak occurs much more frequently, sub-dividing by re-explosion from the smaller particles, represented at "c". With lower percentages of carbon there is less forking of the heavy lines of light and the sparks are thrown from their source of heat under similar conditions of wheel speed and pressure. In the higher carbon steels, the iron lines are practically eliminated and the carbon explosions and subdivisions increase in quantity, causing a beautiful display. The sparks occur near the source of heat as at "d".

All high speed steel contains, in addition to carbon, other alloying elements, chiefly tungsten, chromium and vanadium but while this class of steel may contain anywhere from 0.50 to 0.75 per cent carbon, the spark streaks show no characteristic trace of the carbon spark. It is probable that the carbon is so thoroughly combined with these alloys that it is held in solution thus preventing its spark. High speed steel sparks follow a straight line similar to iron except that the luminous portion of the streak of light is much more abrupt as at "e". In addition there is a char-

acteristic explosion and forking, distinct from the broad iron streak. The color is very dark reddish-yellow due to the high content of tungsten. We have no evidence as yet that chromium or vanadium may be detected by the spark test.

The manganese spark is widely different from the carbon spark in that it seems to shoot or explode at right angles to its lines of travel. Each dart is divided and subdivided into a number of re-explosions which also explode at right angles to their lines of direction. A splendid illustration of the manganese spark may be found in cast iron that is high in manganese. The spark is easily recognized by its branching and distinctly characteristic appearance, represented in "f".

Original "Mushet" steel was selected for the next figure because it contained about 14 to 17 per cent tungsten, about 2 per cent manganese and about 2 per cent carbon, illustrated at "g". With all of these elements combined with iron, we should expect each of the elements to show its characteristic sparks but to our disappointment we find only a red streak of light similar to that of cast iron and at times not even a manganese spark. This steel was selected to demonstrate the limitation of the spark test. However, in such a steel, manganese is more or less segregated and in grinding we occasionally run into a so-called "nest" of the manganese and then a beautiful display of the manganese spark. It is well to state that Mushet steel is not in general use since the introduction of the modern high speed steels.

Tungsten magnet steel was selected for the last figure because of its distinctly characteristic spark and the ease with which it may be tested. The spark is quite similar to that of high speed steel but due to the lower percentage of tungsten the streak of light is much brighter and contains a larger quantity of abruptly luminous explosives, and an occasional manganese spark at "h". The explosions occur at a shorter distance from the wheel. We find in testing a number of permanent magnets of varying analysis that the spark resembles that of carbon steel. Analysis indicates that chromium is the predominant element but unfortunately we are not able to detect this element by the spark test.

Types of steel and ranges of carbon may be determined to a fair degree by the spark test if the sparks of several steels of known chemical analyses are used as standards for comparison.

Proper comparison may be illustrated by touching two dissimilar steels to the wheel at the same time, then by using bars of the same steel, etc. Select several steels of known chemical analyses as standards, mark them for identification and arrange for their safe keeping. Experience is necessary before close distinctions can be made by the spark test. It requires considerable experimentation before one is absolutely sure of his opinion.

Many firms have trained their men to use the spark method as a check. One concrete illustration will suffice: 0.15 per cent carbon steel, cold drawn, was being made in an automatic machine when, very suddenly, several high carbon steel rods went through destroying about \$400.00 worth of jig tools. Upon examination these bars were found to contain 0.70 per cent carbon. Thereafter, this company adopted spark testing. If a bar varied from the standard it was not used.

The characteristic spark of many steels is so clearly distinct that for sorting types of steel only, a standard is not necessary. This test has varied application; for instance, annealed tool steel has more or less of a decarburized surface, meaning the carbon has been removed in the process of annealing. The surface of the metal has been reverted to its natural state, that of iron, therefore the spark will show decarburization by the iron spark indicated at "a", Fig. 73. This test will also roughly determine the depth of the decarburized zone. It will show if the tool maker has removed all of the decarburized material and may also be used to detect decarburized soft spots. Remembering that all metals are more or less decarburized on the surface, one can see that metal should never be tested on the surface. Always test on the ends of rods, etc., and be sure to remove enough metal to get under the skin to the bar itself. The spark test will distinguish carburized material by the high carbon spark as at "c" or "d".

The spark test is useful in determining the quality of the metal in welded parts. For instance, many welds fail because they are hard and brittle, and are impossible to machine. The reason for this condition may be too much carbon. If iron at a welding temperature is in contact with carburizing material it will absorb carbon in proportion to the time it is in contact with such material. If the metal is carburized, it will show the carbon spark in proportion to the increased percentages of carbon as "b", "c", or

“d”, Fig. 73. On the other hand if the metal so welded should be a medium or high carbon steel that has been decarburized in welding, the sparks of the decarburized area will appear as in “a”.

In making malleable cast iron one of the objects in annealing is to change the combined carbon to temper carbon. The process usually decarburizes the surface, as is easily shown by sparks from the surface metal as at “a”. The inner portion of the metal will show sparks somewhat similar to carbon or tool steel.

The necessity of judging accurately and speedily the grade, or carbon content, of a chance bit of metal arises daily in most every shop. A workman in searching for an odd piece to fit an emergency can satisfy his wants if he has some knowledge of the kind of iron or steel in hand. For this purpose the spark test is of great assistance and is always quickly available. It must be admitted that veterans in the service of the machine shop many times are able to tell the composition of a piece of metal by the “heft” or the “feel” of it or by some other more or less intuitive sense which one may acquire by long experience. Although many times in the right, a decision by this method cannot entirely satisfy a critical workman, or prove reliable in an unfamiliar case. Judgment should be given a more definite basis for selecting the metal, such as the spark test.

## LECTURE III

### STRUCTURAL CHANGES ON SLOW COOLING

Before we discuss annealing, normalizing, the reasons for quenching, etc., let us look at the iron-carbon diagram. It pictures the whole story of steel, iron and iron alloys. When several metals are heated together until molten, they are in a "liquid solution," much the same as sugar in water. In cooling, the liquid metal solidifies or "freezes," the metals having the highest freezing point being the first to solidify. The metals which have a lower freezing point become solid or freeze at a lower temperature. When the entire melt has cooled into a solid mass the metals may exist in the form of a "solid solution" or a "mechanical mixture" depending on whether or not the metals are soluble (can be dissolved) in one another in the solid state. In a liquid solution of sugar in water, one cannot see the sugar. The same is true of a solid solution, one cannot see the compounds that compose a solid solution, not even with a very powerful microscope. In the "mechanical mixture," like a liquid mixture, the compounds composing the mixture can be distinguished. Chemistry shows us that when liquid solutions freeze, one of two things happens: (1) the ingredients continue to remain in solution in the solid state as a solid solution, or (2) the ingredients pull away from one another or "separate out," to form a mechanical mixture.

To picture these conditions and then to lead into the iron-carbon diagram, we will first consider the gold-silver system which is a simple example of metallic solutions. Gold has a great chemical affinity for silver, i. e., the gold ring you may have on your finger is made of a definite quantity of gold and of silver, so intimately mixed together that no microscope can distinguish the gold from the silver, because the gold and the silver together form a solid solution. Let us get a concrete picture of this idea and perhaps we will have a better conception of what follows in the treatment of steel.

If pure gold be placed in a crucible and heated to a temperature above its melting point, 1943 degrees Fahr., it will become liquid. If pure silver is added to the crucible the silver will start melting at 1761 degrees Fahr., and the liquid would be a "liquid

solution" of gold and silver. Chemically, they like each other so well that when cold they remain together as a solid solution. These metals each have definite melting and freezing points as above indicated. Fig. 74 shows diagrammatically all of the possible alloys of gold and silver. From this curve it may be noticed that when silver is alloyed with gold, melting and freezing points of the solution are lowered as the percentage of silver is increased. The left hand verticle line represents 100 per cent (pure) gold, and the right hand verticle represents 100 per cent (pure) silver. Horizontal lines represent temperature. The two curves "a" and "b" are drawn between the freezing point of pure gold and that of pure

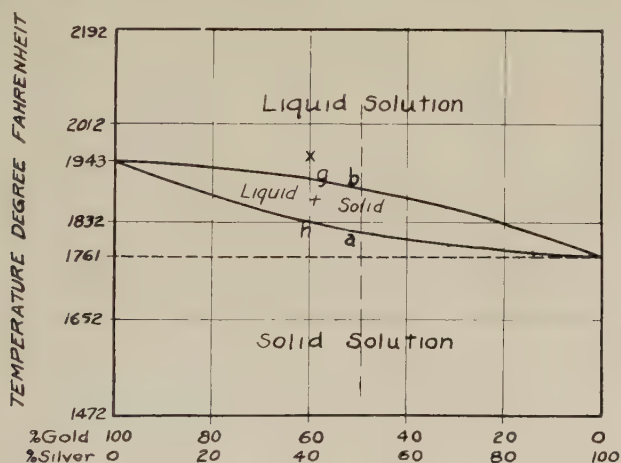


Fig. 74—Constitution Diagram of the Gold-Silver System.

silver. Let us consider a definite quantity of both gold and silver as being melted together in a crucible to form a liquid solution, then study the freezing points of the solution from the constitution diagram. Say we have 40 per cent gold and 60 per cent silver and commence cooling the molten solution at "x." At the temperature indicated by "g" on curve "b," freezing commences. When cooled to temperature "h" on line "a," freezing is complete and the mass forms a solid solution containing 40 per cent gold and 60 per cent silver. This alloy does not freeze at just one temperature, the way molten gold or silver freezes when cooled alone; the alloy freezes over a range of temperature, in this case between temperatures "g" and "h." In like manner, the freezing of any alloy of gold

and silver can be traced on this diagram. If an alloy of gold and silver at room temperature were heated, it would start to melt at a temperature represented by line "a," and would be entirely molten at the temperature shown by line "b."

We may now pass on to a more complex system, for example, a solution of salt and water. It is common knowledge that water may be found in any one of three states, water (liquid), ice (solid), and steam (gas). We also know that water changes its state at a very definite temperature, from a liquid (water) to a solid (ice) at 32 degrees Fahr., and incidentally melts at the same temperature. We also know that water changes its state from a liquid (water) to a gas (steam) at 212 degrees Fahr. If we add salt to

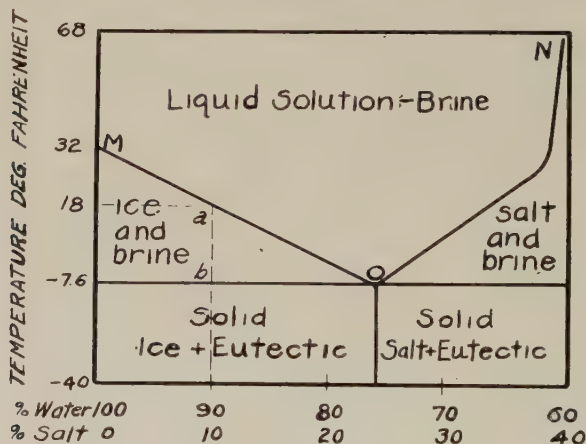


Fig. 75—Constitution Diagram of the Water-Salt System.

water it lowers its freezing point, similar to silver lowering the freezing point of gold. Salt is thrown on slippery sidewalks in winter to prevent freezing of water by lowering its freezing point. Also salt and ice are used around ice cream freezers to produce a liquid that is cold enough to freeze the cream.

To illustrate the effect of varying percentages of salt in water Fig. 75 is presented. M represents the freezing of water (32 degrees Fahr.), O represents the "eutectic." The term eutectic is applied to the alloy or solution having the lowest melting point possible of a given series of compounds. The line MO represents the lowering of the freezing point of water as the percentage of

salt is increased to the "eutectic" composition 76.5 per cent water and 23.5 per cent salt. N represents the freezing point of salt, therefore the line NO represents the increase of temperature at which salt freezes out for percentages of salt above the eutectic composition.

If we freeze pure water we have a solid block of ice made up of ice grains (crystals). If we cool molten salt we have a solid mass of salt grains. Let us mix the two together in any proportion, say 90 per cent water and 10 per cent salt, thoroughly dissolve the salt in water and study the results. The salt and the water form

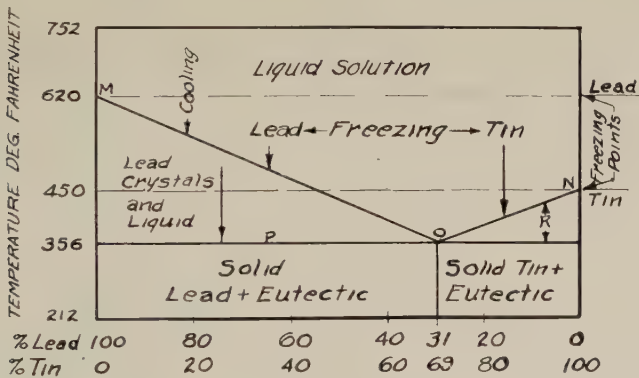


Fig. 76—Constitution Diagram of the Lead-Tin System.

a liquid solution, often called "brine." Suppose this liquid be cooled. Unlike gold and silver, salt and water are not entirely soluble in one another in the solid state. The brine will remain liquid until cooled to about 18 degrees Fahr., point "a" on the line MO, at which the water will begin to form ice grains and the remaining liquid will continue enriching itself with salt up to the "eutectic" proportion of 23.5 per cent salt. When at a temperature of 7.6 degrees Fahr. below zero, line "b," the mass will become a solid, not a solid solution like gold and silver, but an aggregate or mechanical mixture made up of individual ice grains and eutectic grains. The eutectic grains contain the proportion of 23.5 salt and 76.5 water. If the exact eutectic proportion of salt be added to water, the brine will remain liquid until it is cooled to -7.6 degrees Fahr. at which temperature it will freeze. The solid will be composed entirely of eutectic crystals. If the salt content

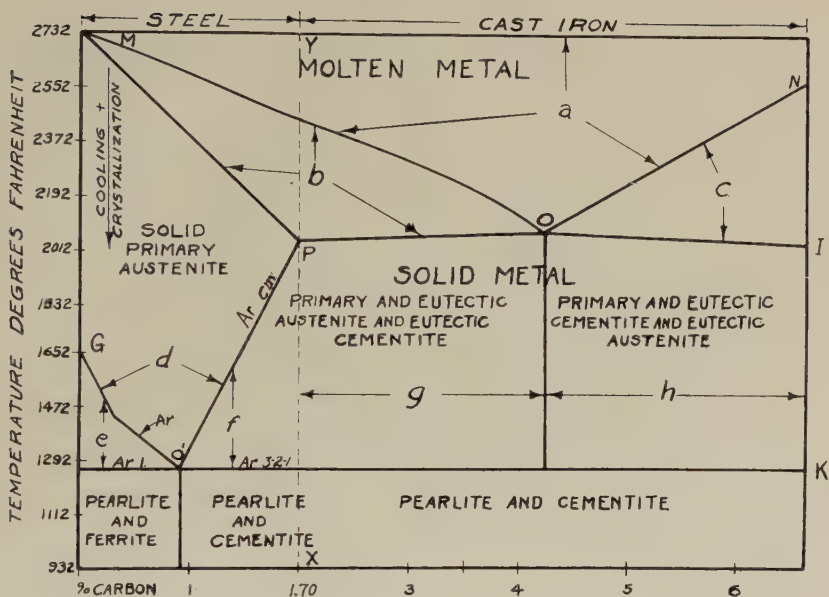
is greater than the eutectic composition and the brine is cooled to a temperature intersecting the line ON, the excess salt above the eutectic percentage will freeze in the form of salt crystals and the liquid will continue discarding the excess salt until it reaches the eutectic proportion of salt and water at  $-7.6$  degrees Fahr. At this temperature the entire mass will become a solid made up of salt and eutectic grains. The eutectic itself is made up of grains containing salt and ice in intimate contact, a mechanical mixture.

### LEAD AND TIN SOLUTIONS

The alloys of lead and tin represent more clearly the freezing of metal, and they exhibit the same eutectic phenomenon that salt solutions exhibit. Fig. 76 shows what happens in cooling a lead-tin alloy. It is similar to the freezing of salt and water, except that when the mass is cold and in a solid state, it is made up of grains of lead or tin and the lead-tin eutectic in proportion to the percentage of each element present.

### IRON-CARBON SYSTEM

The iron-carbon alloys exhibit all the changes found in the gold-silver, and the lead-tin systems. In addition there is another important change, the separation of ferrite, pearlite and free cementite (iron carbide). The writer has attempted to simplify the iron-carbon diagram in Fig. 77 so non-technical men may better visualize the changes that take place on cooling iron and steels. The reader is especially interested in the steel section of this diagram. In order that we may have a better conception of the solidification changes that occur, a brief explanation of the cooling of the metal will greatly assist us. Let us refer to the part of the diagram marked "a." The metal in this space is a molten, liquid solution of iron and carbon, similar to the liquid solutions heretofore mentioned. The point O is the eutectic of iron, containing about 4.30 per cent carbon. The condition of metal in areas "b" and "c" is similar to the freezing of water and salt, also lead and tin. In these areas the metal is partly frozen and partly liquid until it reaches the lower temperatures indicated by the arrow points "b" and "c," line MPOI. All metal in this system becomes solid below the lowest line POI.



Refer to the space marked "d" in which we are more directly interested. Wrought iron becomes solid at 2732 degrees Fahr. while steel of about 1.70 per cent carbon remains partially liquid until it reaches temperature P at which it is entirely solid. Upon solidification, the newly formed grains grow larger as the metal cools to the two lines GO' and O'P. It would be well to keep in mind that the carbon is in solution with the iron regardless of grain size and will so remain as long as the metal is at a temperature above the lines marked GO'P. This is a solid solution of iron and carbon called "austenite." When the metal cools to a temperature intersecting the lines indicated by GO'P, a slight evolution of heat takes place due to an allotropic change in the iron. At this point the carbon becomes active. It does not like being spread out all over the iron so it begins to assemble into distinct groups or areas and retains a portion of the iron as company. Through the range marked "e," free ferrite continues to separate out as the temperature is lowered down to Ar<sub>1</sub> temperature. The carbon and some iron remain as austenite until the Ar<sub>1</sub> is reached. A similar occurrence takes place in the section

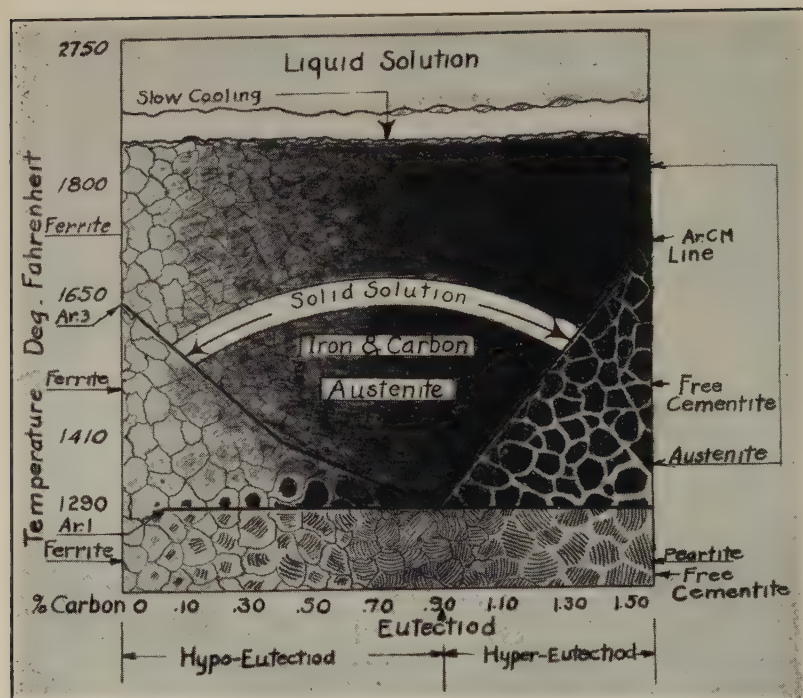


Fig. 78—Iron-Carbon Constitution Diagram for Steels Only, Showing Structural Changes on Cooling.

marked "f" except that the excess carbon is discarded in the form of free cementite. (See Fig. 28c)

Cooling of the metal to the  $Ar_1$  line may be likened to the separation of ice and brine, or lead and tin. The change at  $O'$  is similar to the eutectic  $O$ , or the ice-brine eutectic, but it is a recrystallization taking place entirely in the solid state. It is called the "eutectoid." Heat is evolved during this change (recalescence). The grains of austenite in area "e," change through martensite, troostite and sorbite (intermediate structures explained later), into pearlite. In area "f" on slow cooling through the  $Ar_{3-2-1}$ , the free cementite remains unchanged, but the austenite changes through martensite, troostite and sorbite into pearlite.

The reader will recall that "ferrite" is the structural term for pure iron, as in Fig. 28. Cementite is iron carbide, a very hard substance containing 6.67 per cent carbon and 93.33 per cent iron, shown in Fig. 28c. Pearlite is a combination of ferrite and

cementite in which these two constituents exist in alternate plates or lamellae. It contains 0.90 per cent carbon, and is shown in Figs. 28a and 28b. To simplify discussion, the  $Ar_2$  transformation has been omitted. Iron heated through the  $Ar_2$  range becomes non-magnetic, but no structural change occurs at this temperature.

Fig. 78 shows these reactions schematically, i. e., the critical changes that occur on cooling. In this drawing the carbon in solution is represented by solid black at the right, shaded off to the left as the carbon content decreases and as the iron content increases. The large grain structure in the austenitic areas represents iron or steel cooled from a high temperature and is drawn in this fashion to impress the thought that large grains formed at high temperature will continue to remain large when in the cold state. On slow cooling from the  $Ar_3$  through the  $Ar_1$  ferrite separates out of steel containing less than 0.90 per cent carbon, and the carbon and some iron remain as austenite, indicated by the black grains just above the  $Ar_1$  temperature. Austenite just above the  $Ar_1$  contains just 0.90 per cent carbon (eutectoid proportion). In steels containing more than 0.90 per cent carbon (hypereutectoid steel), some carbon and some iron separate out below the  $Ar_{cm}$  line as free cementite. Some iron and carbon remain in solution as austenite (heavy black grains.) Just at the  $Ar_1$  the austenite contains just 0.90 per cent carbon. In cooling from the  $Ar_{cm}$  to the  $Ar_1$  temperature, cementite continues to be rejected, as indicated by the increasing size of the white lines. When the metal cools through the  $Ar_1$  the austenite is changed through martensite, troostite and sorbite into pearlite. Pearlite is shown by the lamellar plates. Steel containing 0.90 per cent carbon (eutectoid steel) is entirely pearlitic when slowly cooled; steel containing less than 0.90 per cent carbon (hypoeutectoid steel) is composed of pearlite and ferrite; and steel containing above 0.90 per cent carbon (hypereutectoid steel) is composed of pearlite and cementite.

If these large grains are reheated to just above the  $Ac_3$  or the  $Ac_{3-2-1}$  line the reversal of the changes just described will take place. Iron and carbon will form the solid solution austenite, and a recrystallization will take place. The large grains will be changed to fine grains. When so changed and again allowed to cool through the critical range the austenite will again

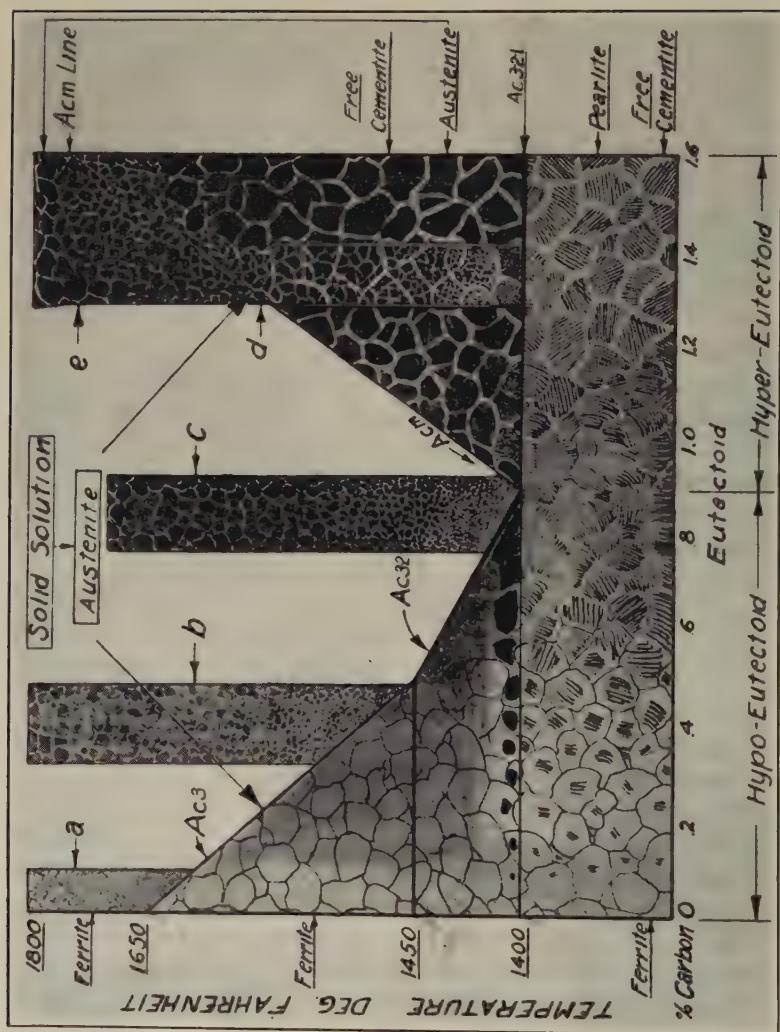


Fig. 79.—Iron-Carbon Diagram for Steel, Showing Structural Changes on Heating.

change through martensite etc., into pearlite, but the size of the pearlite grains will be small, since the temperature of reheating above the  $Ac_3$  was not high enough to cause grain growth. The  $Ar$  changes on cooling are shown in Figs. 77 and 78, and the  $Ac$  changes on heating are shown in Fig. 79.

To repeat, when steel is cooled from a temperature well above the  $Ac_3$  or  $Ac_{cm}$  and cooled slowly, the grains will be very large.

When steel is heated to just above the  $Ac_3$  (for a steel of under 0.90 per cent carbon) or the  $Ac_{3-2-1}$  (see Figs. 77, 78 or 79 for a steel of over 0.90 per cent carbon), soaked at that temperature and slowly cooled, the grains will be small. Steel containing less than 0.90 per cent carbon is termed "hypoeutectoid" steel. Steel of over 0.90 per cent carbon is "hypereutectoid" steel.

In the discussion of the cooling of ingots and forgings the reader will recall that the term Ar (recalcescence) designates a physical change that takes place during cooling. The Ac (decalcescence) designates such a change during heating of the metal. The critical points do not occur at the same temperature in heating as in cooling. The metal is rather reluctant to change its physical state, so that on heating, the Ac points occur at a temperature somewhat higher than might be expected. Likewise, the Ar temperatures on cooling are lower than would be supposed. In any case the Ac is higher than the Ar. To aid the memory, on heating, the Ac lag (from the French word *chauffage*) necessitates a higher temperature; on cooling, the Ar lag (*refroidissement*) necessitates a lower temperature. The difference in temperature between the Ac and the Ar varies. In some cases it is as great as 75 degrees Fahr. In general discussion, the terms  $A_1$ ,  $A_2$  or  $A_3$  are often used, without specific reference to the Ar or Ac. In that case, it is understood that the reader will remember the phenomenon of lag and apply the Ac or Ar temperature for a specific job.

Fig. 79 shows the Ac (heating) changes schematically, with special reference to the grain growth. Referring to the pearlitic section below the  $Ac_1$  point, the structure is made up of grains of ferrite and pearlite in hypoeutectoid steel and pearlite and cementite (iron carbide) in hypereutectoid steel. Slowly cooled steel is therefore a mechanical mixture of iron and carbon etc., and not a solid solution. Let us reheat a piece of large grained steel to break up the large structure. Reheating will cause the carbon to disperse into the iron above the  $Ac_3$  or  $Ac_{3-2-1}$ , to form a "solid solution." When again cooled the carbon will be reprecipitated as pearlite or cementite. The grains will be small.

Before attempting to create these changes let us try to develop a little imagination as to just what occurs. Suppose we had in front of us a block of concrete floor or side walls like that used

in our modern buildings. It will possibly be made up of grains of soft limestone, hard marble and harder granite held together by cement. The surface is highly polished to bring out the different colors and orientation of the grains. A similar picture might be developed from slowly cooled steel.

Let our imagination assume that this block has critical temperatures similar to iron or steel. Upon being heated to above its critical points these grains will break up into a fine powder, intimately mixed together and with the cement but without changing the outer shape of the block. If you can conceive of such a possibility then you have some conception of what takes place at the transformation points of steel.

If we now concentrate our attention upon the left hand side of the chart, Fig. 79, it may be noted that the iron grains (light in color) contain no carbon. It may also be noted by following the grain structure upward that there is no marked change in structure at the  $Ac_1$  point. Iron becomes nonmagnetic at the  $Ac_2$  point but with no change in structure. On further heating the large grains are completely broken up into a fine state at the  $Ac_3$  point. With increase of temperature from this point the grains grow in proportion to height of temperature above the  $Ac_3$ .

Let us follow a 0.40 per cent carbon (hypoeutectoid) steel on being heated. In passing through the  $Ac_1$  point the areas of pearlite transform into austenite, indicated by the heavy black grains above the  $Ac_1$ . With further increase of temperature the austenite begins to disperse through the grains of the free ferrite (iron) as indicated by the shading of the hypoeutectoid section, and is completely spread or mixed with the iron grains (like mixing sugar in coffee). In heating slowly from the  $A_1$  through the  $A_3$ , transformation takes place and the ferrite passes into solution as austenite, obliterating all the large grain structure. New grains are "born" (so to speak). The carbon is now in solution with the iron. With further increase in temperature these minute grains increase in size in proportion to increase in temperature as indicated at "b".

Let us now see what happens to a 0.90 per cent carbon steel (eutectoid composition). Complete transformation takes place at the  $Ac_{3-2-1}$  line. (Refer to Fig. 77, the  $Ac_{3-2-1}$  is line O' K.).

Upon further heating the grains increase in size as indicated at "c".

If we heat a coarse-grained 1.35 per cent carbon (hyper-eutectoid) steel it may be noted when the metal reaches the  $A_{c_{3-2-1}}$  point, the transformation of pearlite into austenite occurs. This is indicated by the extremely black grains, and the grains of fine structure bounded by free cementite which boundary is not materially disturbed at this temperature. On further increase in temperature to above the  $A_{cm}$  temperature, the austenite readily absorbs the free cementite. Now let us go back to the  $A_{c_{3-2-1}}$  line and follow the recrystallization. Like the hypoeutectoid steel above the  $A_3$  point, the grains increase in size with the increased temperature above the  $A_{3-2-1}$ . In recrystallizing, new grains are born within the cementite network. The cementite in the network will be very slowly absorbed at temperatures between the  $A_{3-2-1}$  and the  $A_{cm}$ , but at the  $A_{cm}$ , the cementite dissolves in the austenite. In heat treating, a large cementite network can be economically broken up only by reheating to above the  $A_{cm}$  temperature. This will cause some grain growth. Quenching from above the  $A_{cm}$  either holds the cementite in solution, or causes it to be very finely divided and evenly distributed throughout the steel. Reheating to just above the  $A_{c_{3-2-1}}$  will refine the enlarged grain structure without disturbing the finely dispersed cementite.

One can determine the desired internal form of the steel from the chart, Fig. 79. The steel is then heated so as to attain the desired structure and the attempt is made to retain the structure by quenching. The more rapid the quench the more of the high temperature structure will be retained at room temperature. Fig. 80 is a photomicrograph of a piece of steel carburized at about 1750 degrees Fahr. for several hours, a temperature well above the  $A_3$  or the  $A_{cm}$ . The left hand portion is made of large grains of pearlite and free ferrite. The black band is eutectoid steel composed entirely of pearlite. The black areas at the right are pearlite grains bounded by a network of free cementite.

#### MICROCONSTITUENTS OF STEEL

In discussing the iron-carbon diagram, it was stated that when steel is heated above the  $A_3$  temperature range, the carbon and iron dissolve in one another to form a solid solution termed

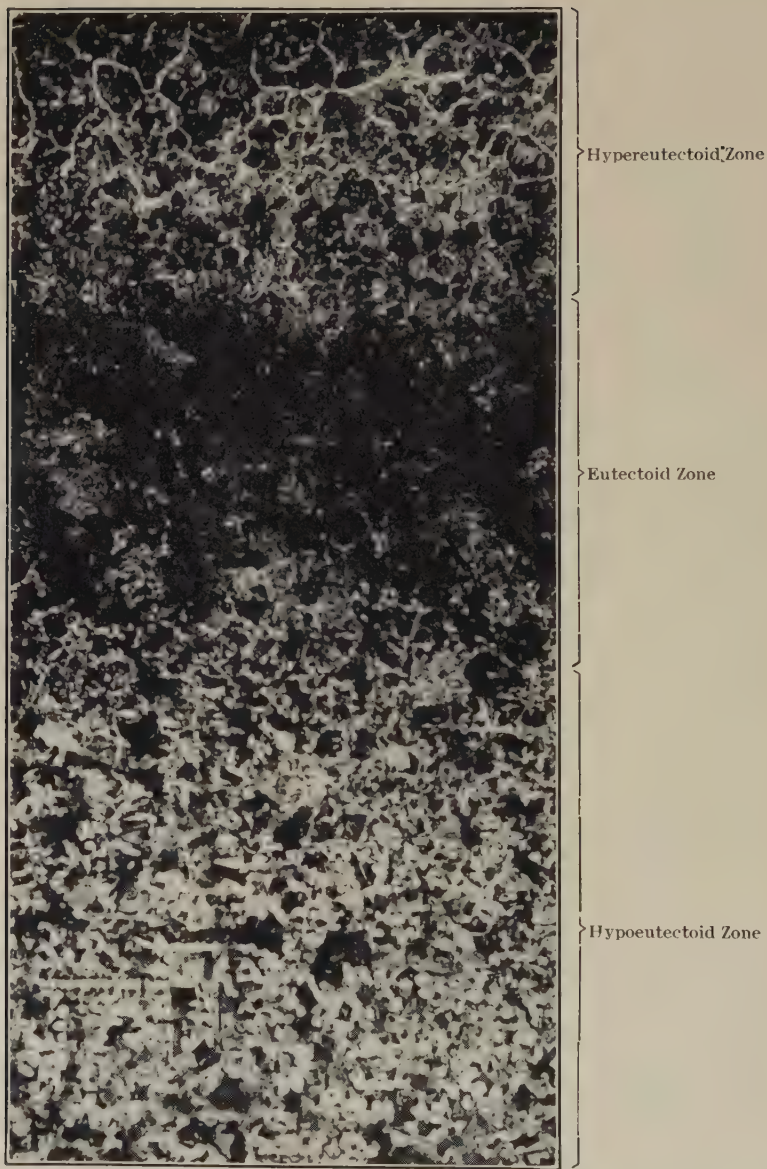


Fig. 80—Photomicrograph of a Carburized Section, Showing from Bottom to Top (1) the Hypoeutectoid Zone Containing Large Grains of Free Ferrite, (2) the Eutectoid Zone Containing Only Pearlite, (3) the Hypereutectoid Zone Containing a Network of Free Cementite.

“austenite.” Further, when austenite is slowly cooled from above the Ac range, it breaks down or decomposes through a series of intermediate structures martensite, troostite, and sorbite into (1) ferrite plus pearlite in hypoeutectoid steels (steels containing less than 0.90 per cent carbon), (2) pearlite only in eutectoid steels (steels containing 0.90 per cent carbon), or (3) pearlite plus cementite in hypereutectoid steels (steels containing more than 0.90 per cent carbon). It has been shown all along that structural changes in iron and steel depend on temperature, time and alloy content. For the present, we shall eliminate alloy steels from consideration and discuss only plain carbon steels except to mention the tendencies of alloys in a few specific instances.

The complete decomposition from austenite to pearlite requires slow cooling. More rapid cooling to room temperature results in the retention of martensite, troostite, sorbite, even some pearlite, or a combination of these structures. The line of demarcation between these structures is not at all sharp. More often, several structures exist in the same piece of steel all at the same time. Again, these structures, especially troostite, sorbite and pearlite can be formed (and with greater regularity) by rapid quenching from above the  $A_3$  to retain martensite, followed by a tempering (drawing) treatment at a lower temperature, say 500 or 800 degrees Fahr. for a time, say 15 minutes, one hour, etc., depending on the size of part being treated.

These structures will be discussed separately, and photomicrographs of each given so the reader may picture each structure in his mind. But few of us have a microscope at hand, and even then few of us care to be bothered by the laborious process of polishing, and etching samples of steel with chemicals for microscopic examination. Either fortunately or unfortunately the microscope and the photomicrograph offer the only means of visualizing structural changes that are the result of thermal treatments. The writer asks the reader to bear with him, believing that the structures about to be pictured will enable the reader to associate the structure with physical properties, thermal treatments and approximate chemical analysis and give the reader a vehicle by which he may better organize his thought and think out the “why” for the results of processes in daily use. These structures and their pictures (photomicrographs) are the principal means at hand for

writers in the literature to portray their meaning to a reader, and it is hoped that the reader will peruse the literature for his own benefit.

### *Austenite*

Austenite is the solid solution of carbon in iron formed by heating a piece of steel to above the  $A_3$  temperature range. Austenite is a difficult structure to retain at room temperature unless the steel contains a large percentage of alloy, such as manganese, or chromium. Fig. 81 shows a typical austenitic structure in steel containing 12 per cent manganese (Hadfield's steel). Austenite is usually large grained due to long soaking of the specimen at above the  $A_3$  temperature range. It is nonmagnetic, and very tough. Practically, austenitic steel cannot be machined except by grinding.

Austenitic steel is characterized by high tensile strength and unusually great ductility. The tensile strength is often around 125,000 pounds per square inch with an elongation in 2 inches of 35 to 40 per cent. A bar of this material can be bent back and forth on itself several times without breaking and when fracture does occur the metal tears apart instead of breaking off in a clean fashion. Power shovel parts such as clipper teeth and bucket lips for use in handling ore, rock and sand are often made of 12 per cent manganese steel which is austenitic. This steel withstands an immense amount of pounding and cold working. The same type of austenitic steel is used extensively in electrical machinery where nonmagnetic parts are required.

### *Martensite*

Martensite is the usual constituent of plain carbon steel drastically quenched from above the  $A_3$  temperature range. It is the first decomposition structure of austenite. Martensite is the principle structural constituent of hardened steel. Fig. 82a shows a typical martensite. Note the needle-like structure. Fig. 82b shows a very fine grained martensite. It is probably needle-like, but the little needles are so very small that even the microscope could not clearly show them. Martensite is the principle constituent of cold chisel cutting edges, file teeth, and razor blades. It is extremely hard and brittle.

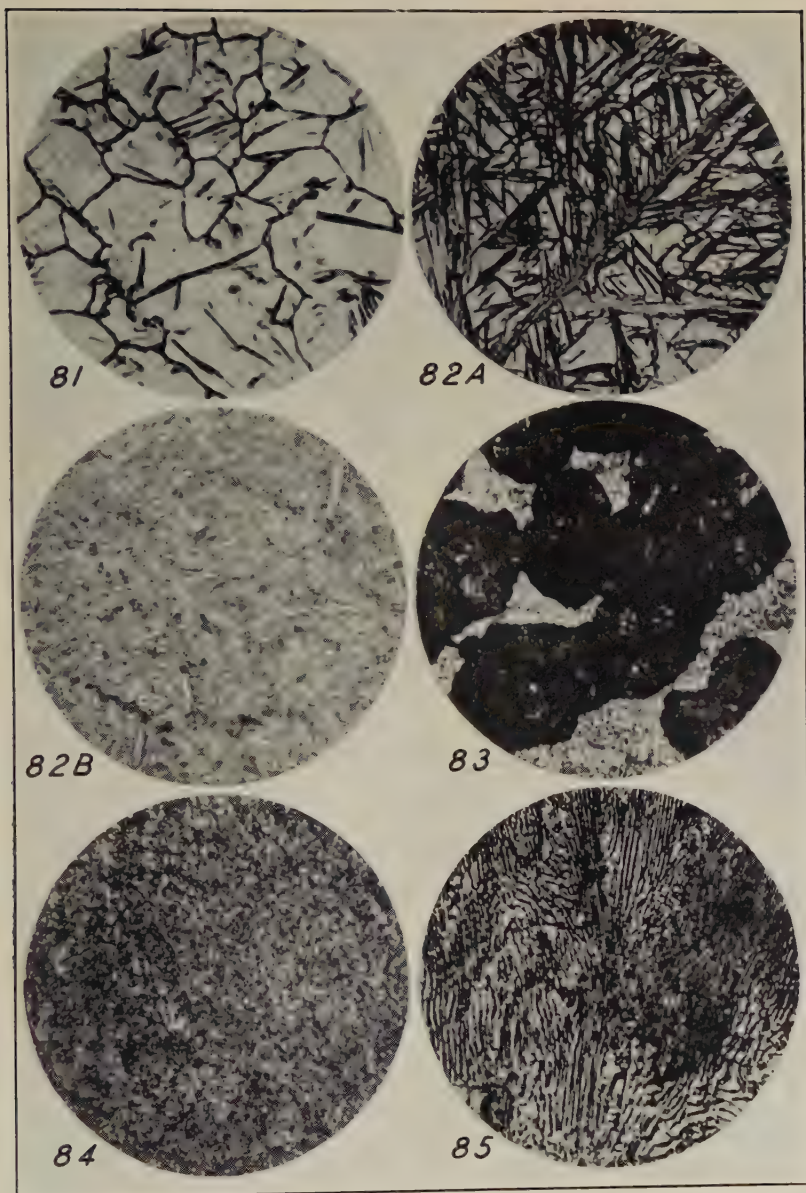


Fig. 81—Photomicrograph of Austenite in Steel Containing 1.25 Per Cent Carbon and 12 Per Cent Manganese, Quenched in Water from 1850 Degrees Fahr.,  $\times 180$ . Fig. 82A—Typical Martensite, Characterized by the Needle-Like Structure,  $\times 200$ . Fig. 82B—Very Fine Grained Martensite. The Structure is Probably Needle-Like But the Needles are so Fine That They Are Almost Sub Microscopic in Size,  $\times 450$ . Fig. 83—Troostite, Showing its Usual Rosette-Like Form. The Lighter Ground Mass is Undecomposed Martensite,  $\times 400$ . Fig. 84—Spherulite, Showing the Tangled Mass of Lines and Dots, Like Pearlite Lamellae in Process of Forming,  $\times 250$ .—Fig. 85—Lamellar Pearlite. The Little Plates or Lamellae are Alternately Ferrite and Cementite,  $\times 500$ . Figs. 81, 82B and 85—Courtesy R. G. Guthrie.

*Troostite*

Troostite forms when martensite decomposes. It seldom exists alone, but is usually accompanied by quantities of martensite or sorbite, or both. Fig. 83 shows a typical troostite as a sort of black rosette studding a field of the needle-like martensite. Troostite can be formed in higher carbon steel by fairly drastic quenching, or by first quenching the steel from above the  $A_3$  temperature to retain martensite, then by tempering at about 600 to 650 degrees Fahr. to decompose the martensite into troostite. It is of technical importance on account of its combination of hardness and a moderate amount of toughness. It occurs in cold chisels at the zone immediately back of the hard martensitic cutting edge and ahead of the tough shank.

*Sorbite*

Sorbite represents the toughest condition of a given steel. It can be formed by moderately slow cooling from above the  $A_3$ , by the prolonged heating of martensite at about 750 to 800 degrees Fahr., or by prolonged heating of troostite at about the same temperature. Fig. 84 shows a good sorbite. It may be regarded as a tangled mass of pearlite plates or lamellae in the process of arranging themselves in regular alternate plates of ferrite and cementite, like unborn or embryonic pearlite. Sorbite is of great technical importance on account of its excellent combination of strength, ductility and toughness. It is the ideal constituent for motor connecting rods, crankshafts, chisel shanks and power transmission parts not subject to unusual wear or abrasion.

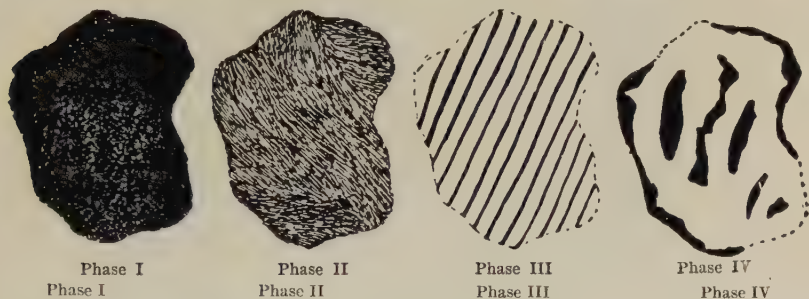
*Pearlite*

Pearlite in the lamellar or plate-like form is shown in Fig. 85. The plates are alternately ferrite and cementite. Pearlite is the eutectoid structure and contains 0.90 per cent carbon in plain carbon steels. Lamellar pearlite is one of the chief constituents of steel castings that have been given a simple anneal. The hard cementite makes pearlite rather hard and brittle. Pearlite has a tensile strength of around 125,000 pounds per square inch and an elongation in 2 inches of 10 per cent. It exerts maximum hardening power of any constituent. Pearlite is not particularly desirable in machinery parts.

Four forms of pearlite are shown in Fig. 86, as it changes from sorbite through lamellar pearlite, into the massive or spheroidal form.

### *Granular or Spheroidized Pearlite*

Granular or spheroidized pearlite is lamellar pearlite heated until the lamellae are drawn together in round balls. We have



Phase I

Phase I

Phase II

Phase II

Phase III

Phase III

Phase IV

Phase IV

Fig. 86—Properties and Kinds of Pearlite.  $\text{Fe}_3\text{C}$  Represented in Black. (After Arnold as Published by Sauveur.)

Phase I—Sorbite Pearlite with Emulsified  $\text{Fe}_3\text{C}$ . Very Dark on Etching. Maximum Tensile Strength 150,000 Pounds Per Square Inch. Elongation 10 Per Cent.

Phase II—Normal Pearlite with Semi-Segregated  $\text{Fe}_3\text{C}$ . Dark on Etching. Maximum Tensile Strength 120,000 Pounds Per Square Inch. Elongation 15 Per Cent.

Phase III—Laminated Pearlite with Completely Segregated  $\text{Fe}_3\text{C}$  Exhibiting a Play of Gorgeous Colors When Lightly Etched. Maximum Tensile Strength 77,000 Pounds Per Square Inch. Elongation 5 Per Cent.

Phase IV—Laminated Pearlite Passing Into Massive  $\text{Fe}_3\text{C}$  and Ferrite. Maximum Tensile Strength 66,000 Pounds Per Square Inch.

seen that the molecules and grains of steel attain certain mobility as the temperature is increased. When oil and water are shaken together, the oil forms little balls or spheroids throughout the water. The spheroids of oil tend to gather together, forming larger spheroids if the emulsion is not disturbed. So in lamellar pearlite, the little plates of cementite try to contract into round balls or spheroids at the proper temperature. The ferrite lamellae tend or try to attach themselves together, or form a ground mass with any quantities of free ferrite that may be present.

Fig. 87 shows a granular pearlite. The cementite occurs in round balls or spheroids. Granular pearlite is formed by the prolonged heating of lamellar pearlite at just under the  $A_1$  critical range, by heating a plain carbon steel at about 1250 to 1300 degrees Fahr. for a period of time. It is soft, very weak and is quite ductile at ordinary temperature. Granular pearlite is chiefly useful in machining high carbon steels. Tool steel of say 0.90 to 1.00 per cent carbon is machinable when the pearlite exists in

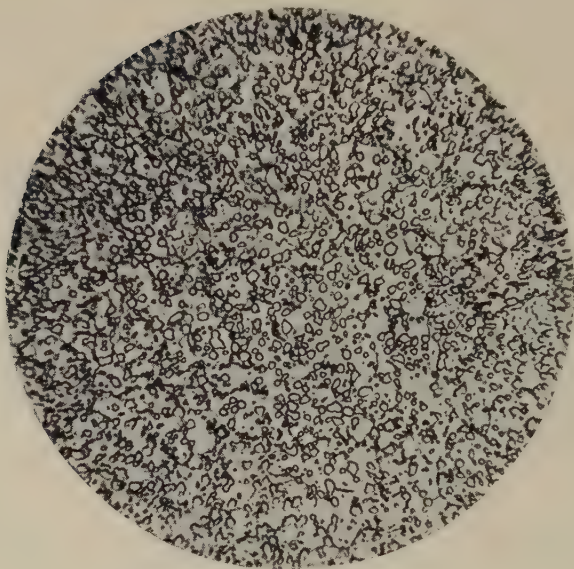


Fig. 87—Granular or Spheroidal Pearlite.

the spheroidal form. The little spheroids of cementite can be cut or torn out ahead of a cutting tool. The spheroidal cementite can be thrown back into solution by heating the tool to above the  $A_{cm}$  temperature, and the tool can then be hardened after being machined. A file (containing 1.25 to 1.40 per cent carbon) is machinable when its structure is granular pearlite.

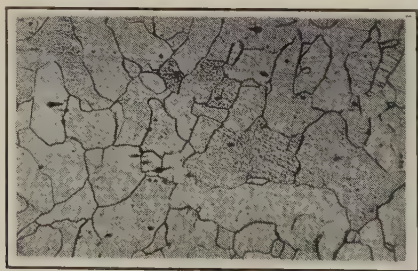


Fig. 88—Ferrite in Ingot Iron.

### *Ferrite*

Ferrite is pure iron. Fig. 88 shows a bar of ingot iron (commercially pure iron) composed entirely of ferrite. As previously

stated, ferrite is very ductile and soft and has a low tensile strength but high elongation (stretch). It has a tensile strength of but about 40,000 pounds per square inch, and an elongation in 2 inches of about 40 per cent.

### *Cementite*

Cementite as previously stated is iron carbide. Fig. 89 shows the cementite network caused by the precipitation of cementite on

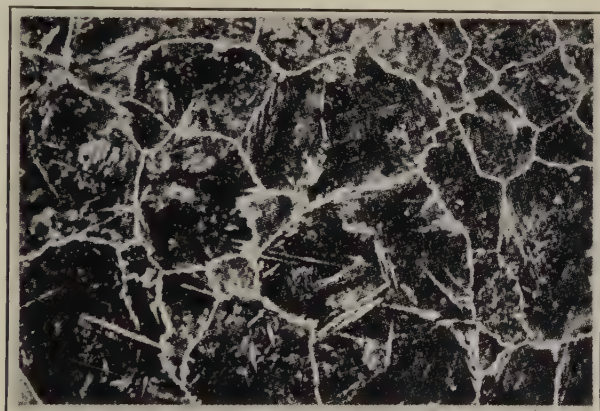


Fig. 89—Cementite Network in a Hypereutectoid Steel Heated for a Time Above the  $A_{cm}$  Temperature. Carbon Content 1.40 Per Cent.  $\times 100$ .

the prolonged heating of a hypereutectoid (above 0.90 per cent carbon) steel at a temperature above the  $A_{cm}$ . It is one of the hardest substances known, and is characterized by a very high tensile strength and extreme brittleness. Its ductility and hardening power are practically nil. Cementite etches black under some circumstances (usually in pearlite) and white in others.

### *Graphite*

Graphite is pure carbon. Fig. 90 shows a typical cast iron in which the graphite exists in crystalline form like little black fish scales, precipitated on cooling in the mold. Fig. 91B shows an annealed malleable cast iron. The carbon is amorphous (called temper carbon), having no particular form as shown by the irregu-

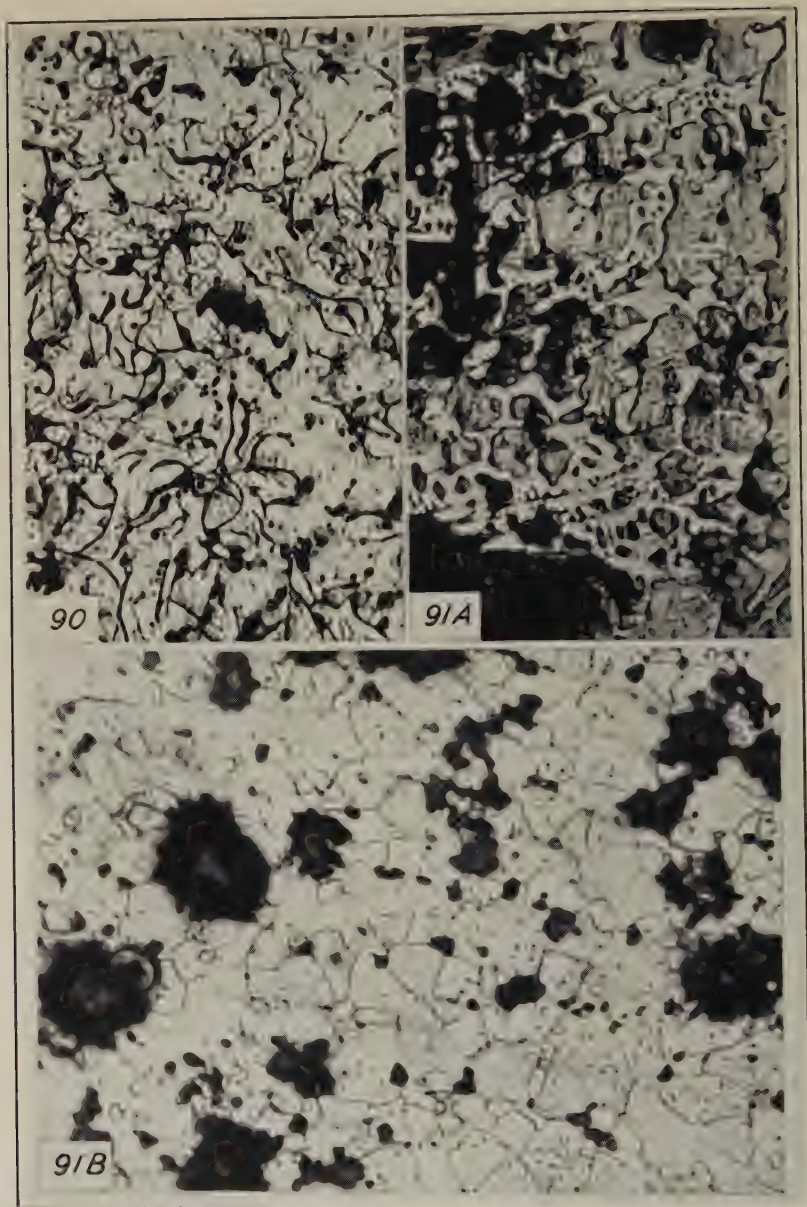


Fig. 90--Cast Iron in Which the Carbon Exists in its Crystalline Form, the Black Scale Like Structure. Fig. 91--Malleable Cast Iron. A--Structure of White Iron Just After Pouring. B--Malleable Cast Iron After Annealing. The White Background is Ferrite. The Shapeless Black Blotches are Colonies of Precipitated Amorphous Carbon.

lar black spots. The carbon was precipitated by a prolonged anneal as will be explained later.

### ANNEALING

There are three distinct purposes in annealing iron or low carbon steel, (1) to relieve all external or internal strains that may be caused by cold working, cold drawing, unequal hammering, or unequal heating or cooling, (2) to produce a uniform crystalline structure throughout the mass of metal, (3) to impart distinct physical characteristics to the metal. There are four distinct purposes in annealing high carbon or hard alloy steel, (1) to relieve all external or internal strains, (2) to impart a uniform crystalline structure throughout the mass of metal, (3) to secure a desirable combination of strength, elastic limit and ductility that it may successfully withstand the strain to which it may be subjected, and (4) to remove hardness that the metal may be more easily machined.

Except for condition 3, these conditions may be imparted to iron or steel if the metal is heated uniformly to about 100 degrees Fahr. above the  $A_3$  critical range as indicated by line A to the left of drawing, Fig. 92, or as shown on the iron-carbon diagram in Fig. 97. Fig. 92 was developed to assist the reader in picturing the annealing process. In the chart, circles represent the crystalline structure as previously outlined in this series. The coordinates in this chart are temperature and time, indicated on the left hand corner. A section of the iron-carbon diagram is located on the temperature scale between 1290 and 1625 degrees Fahr. The diagram represents the cooling curve of carbon steel indicated by the angle line A, terminating in the heavy black line beneath  $Ar_{3-2-1}$  and representing the lowest point of critical range in carbon steels, about 1290 degrees Fahr.

The angles and curves drawn in the central figure are not theoretically located. They are drawn at those angles to show that metal requires time in heating and cooling. The reheating curve indicated by "a" (lower horizontal line of letters) is broken in three places, indicating the three transformation changes (Ac changes) that occur in low carbon (hypoeutectoid) steel upon heating. By following this line across the page, the Ar changes are

shown for cooling. This portion of the curve bears reference to letter "a<sup>1</sup>". The reheating curve of high carbon (hypereutectoid) steel is indicated at "b". Hypereutectoid steel has only one

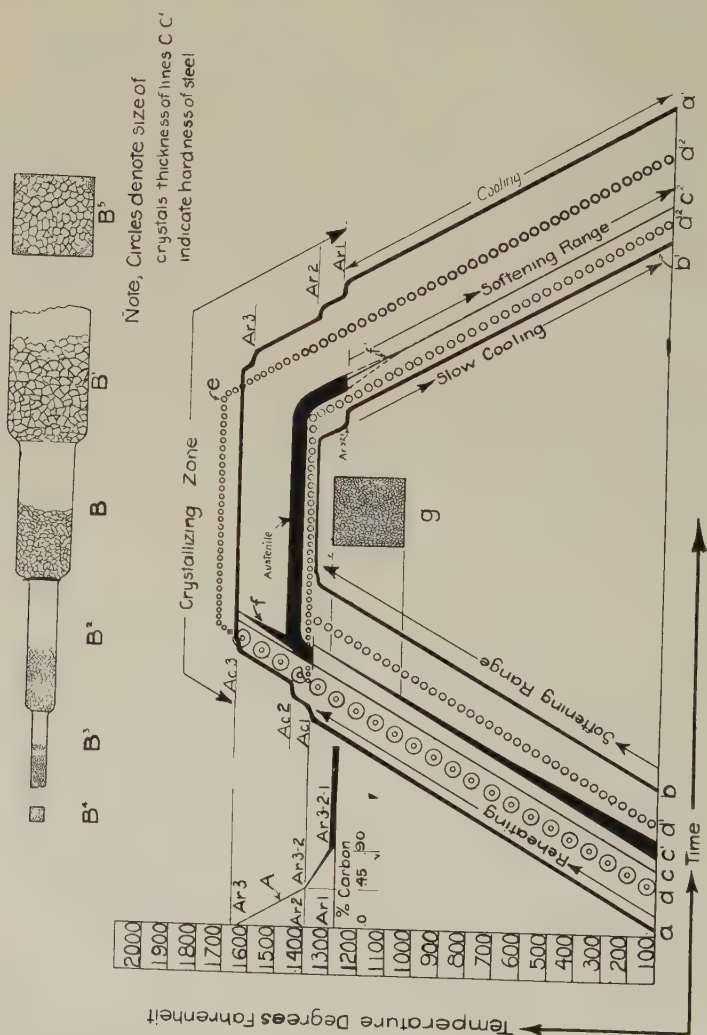


Fig. 92--Schematic Representation of Annealing of Iron and Steel.

transformation point as indicated by  $Ac_1$  (decalescence) on heating, and the  $Ar_1$  (recalescence) on cooling. The lines of circles "d", "d<sup>1</sup>", "d<sup>2</sup>", and "d<sup>3</sup>", represent graphically the size of the grains (crystals). The fine line "e" indicates the minimum hard-

ness of annealed steel. The heavy dark line "c<sup>1</sup>", indicates the maximum hardness of carbon steel by the thickness of the line. The forging represented by B at the top of the figure shows a fairly large sized piece of metal heated to extremely high temperature. Part of the block was placed under a hammer or press. It shows four steps in reduction and the corresponding grain size of each step. Before proceeding further the writer would advise a study of this chart.

This paragraph applies only to hypereutectoid steels. Quite a general opinion exists among practical men that when steel is heated and quenched in water or other quenching medium, it is the quenching liquid that causes hardness. That statement is true only when the metal has been heated above the  $A_{3-21}$  (for hypereutectoid steel) at which temperature the metal changes its state from that of a mechanical mixture, pearlite-cementite, to that of a solid solution of iron and carbon, austenite. When the metal is austenitic, it is in a condition to develop hardness in proportion to the speed at which the heat is removed from the mass in cooling through the  $Ar_1$  point to develop martensite, the hardening constituent. The converging of the hardness line (dotted) at the point "f'", line "c<sup>2</sup>" illustrates the time factor with the steel cooling slowly through the recalescence transformation. Slow cooling decreases hardness since the austenite changes through troostite into sorbite or pearlite. Hence the reason for cooling in the furnace, lime, mica, hot ashes, and other non-heat conducting material is to prevent too rapid removal of the heat from the parts being annealed, thereby avoiding any hardness.

When hot steel is buried in a non-heat conducting material it may not become soft at times, as expected. Have you considered the temperature difference between the hot steel and the material in which is it buried? When the ashes, lime, etc., are cold, they will chill the steel at least until they are heated through. Thin sections may actually harden when cooled in lime that is cold.

With these points in mind, why is it necessary to reheat previously hardened tools, jigs, dies, etc., to a hardening temperature (austenite) in order to soften for machining purposes? When is it possible to reheat such parts or tools to just below the critical temperature  $Ac_1$ ? The following demonstration, quite extensively applied in training industrial groups, should answer these ques-

tions. Heat an old hard file (carbon content about 1.20 per cent) to a softening temperature as indicated at the narrowest point of heavy black line "c<sup>1</sup>", Fig. 92, a dark red heat just above  $Ar_1$  about 1300 degrees Fahr., and quench in water or oil. Air cooling will answer the purpose. If performed correctly one should be able to file, drill, tap, chip, or cut the file. It may even be twisted and bent to the form of a ring. If the treatment has not softened the file then one of two things has happened; either (1) it was heated at too low a temperature to remove the hardness, or (2) it was heated above the critical range ( $Ac_3$ ). Continue this treatment until the file is soft. This treatment spheroidizes the cementite in the file, making it machinable. The quenching of the file from just below the  $Ar_1$  temperature shows that drastic quenching will not in itself impart hardness, as many old-timers believe. It is the temperature that determines the change. The quench retains the changed condition just in proportion to the speed of the quench. A drastic quench retains more of the hardening constituents, and slow cooling permits the hardening constituents (martensite, etc.) to revert back to pearlite and cementite. If the steel has not been soaked at the temperature for the formation of the hardening constituents (above  $Ac_3$ ) how can drastic quenching cause any hardening?

Tool steels contain sufficient carbon to develop maximum hardness when properly hardened, and they will soften when properly annealed. But as the percentage of carbon in iron decreases the hardening power likewise decreases. For steels containing less than 0.90 per cent carbon we have attempted to illustrate that point by a converging of the "hardness" line at "f", a continuation of the lines "c" and "c<sup>1</sup>". The extreme point of this line is intended to show iron or very low carbon steel and to indicate that such metal has very little hardening power. Such metal does not require extreme care in slow cooling in order to anneal. Another purpose of annealing is to remove stresses and to produce a uniform structure.

The varying structure in the forging illustrated at B is characteristic of many forgings. Let us assume that the metal is a low carbon steel and the specification requires annealing. The two sizes of grains or crystals in the forging are illustrated at the line of circles along "d". It may be noticed as the eye follows the

line "d" upward, that there is no change in the size of the larger or smaller grains (line of circles) until the highest point of the critical range  $Ac_3$  is reached. Here the molecular transformation occurs in which all previously large grains are broken up and new grains are born in any portion of the metal attaining the  $Ac_3$  temperature. The time factor is now an important one, as the larger section  $B^1$  and  $B^5$  requires time for heat to be absorbed throughout the mass. When transformation is completed throughout the mass, the next step is cooling. Owing to the fact that this type of metal has very little hardening power, almost any process of cooling may be applied, depending upon the physical properties desired. A simple treatment of withdrawing from the furnace and air cooling would increase its tensile strength and toughness.

In annealing higher carbon steel parts it is simply a question of heating above the critical temperature and cooling slowly in the furnace. Suggested annealing temperatures are shown in Fig. 97.

### *Annealing for the Removal of Stresses*

Heating to just below the lowest point of the critical range  $Ac_1$  is represented by block "g", Fig. 92. Assuming reasonable time for heat saturation followed by cooling slowly, no internal stress will be set up. This is the usual procedure in the cold drawing of wire where the action of cold drawing elongates the soft ductile grains, causing brittleness in proportion to the amount of reduction. If worked beyond certain limits the metal will become so brittle that rupture will take place. After a certain amount of stretch, the metal is annealed below the critical range as above described. Now the question arises, what occurs to the metal at the  $A_1$  temperature that it may be again reduced or cold-worked? This mechanism is shown in the free-hand drawing, Fig. 41. A indicates the grains, stable from hot rolling or annealing. B indicates the grains very much elongated from cold working and therefore in stress. C indicates the grains returned to their usual state after annealing. The metal is thereby prepared to withstand further reduction, hardening, etc. It would be well to remember at this point that any form of cold work will cause distortion of the grains in all types of metal. Cold bending, hammering, peening, straightening, dark red hammering of tools,

hogging machine work, etc., are examples of cold working. Gear and tool manufacturers have learned the value of low temperature annealing cold-worked material before final finishing.

From this drawing one may readily grasp the value of annealing all stressed material. Take chain as one example of many thousand. The so-called crystallized chain develops brittleness because of pounding, twisting, bending over sharp corners of hard

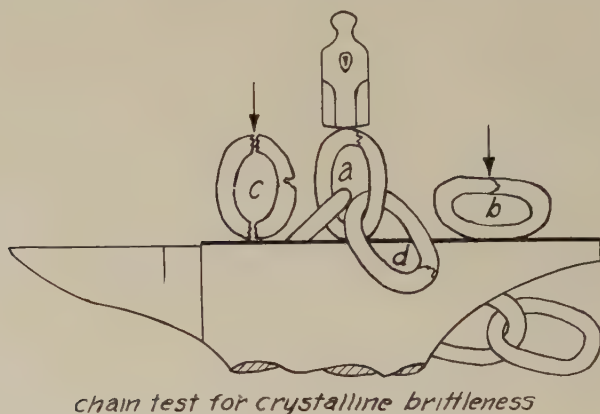


Fig. 93—Chain Tested for Brittleness.

material and particularly because of overloading beyond its elastic limit. Such stresses may be removed as was done to the wire, mentioned above. The grains return to their previous size as indicated at "c" Fig. 41. Such annealing does not break up the large grains, but simply removes stress and prepares the metal for further cold working in service. Uniformity of temperature is just as important in this operation as in all other processes of heat treatment.

### *Chain Problems*

In the industrial plants, mines and quarries where large quantities of chain and other parts of machinery are made out of iron and low carbon steel there is always some discarded would-be crystallized material available for experimentation. Take such a chain for instance, heat a few individual links at different temperatures and air cool them. Then test for brittleness by placing the link with its longest axis perpendicular to the face of the anvil

indicated at "a", Fig. 93. Hit it several blows and note results. A brittle link will crack open like a nut, indicated at "b". If the stresses and brittleness have been removed by annealing the link will bend as indicated at "c", Fig. 94.

In the testing of new chain for brittleness one must give serious consideration to links of chain that are wound or bent cold.

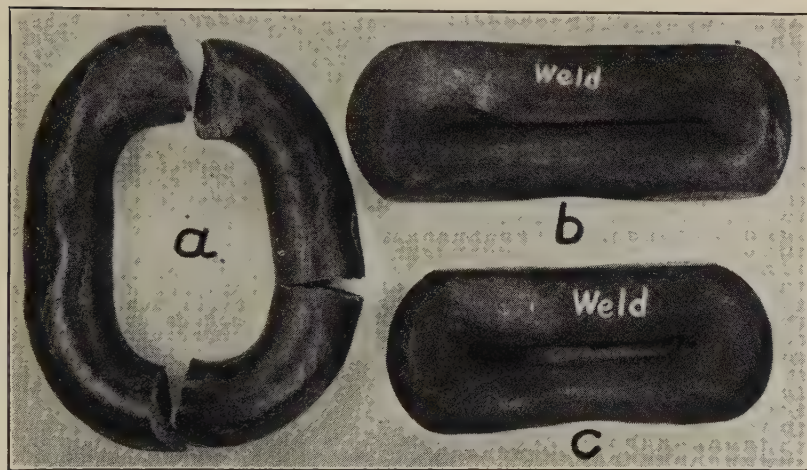


Fig. 94—Chain Links Tested for Brittleness, and Annealed to Restore Ductility.

When tested, such links may crack from the inside out at points diametrically opposite to the weld because that portion of the link will be under stress from bending in the forming operation. If such stresses are relieved by heat treatment, failures will not occur. Carry out the following experiment on a brittle chain. Place a link as indicated at "a", Fig. 93, and crack it open by a few blows of the sledge, as indicated at "b". This leaves link "d" free, so place it in the fire or furnace and heat to above  $A_{c_3}$ , to 1650 degrees Fahr. If the chain is about  $1\frac{1}{4}$  inches in diameter, heat it uniformly and time quench in water for about 4 seconds. Remove and throw it on the floor. When cold and dry, place it on the anvil and test as indicated at "a" and note results.

In such an experiment the chain was heated to above the  $A_{c_3}$  point and time quenched in water for about four seconds. When cold it was flattened together as indicated at "b" and "c", Fig.

94. The question arose as to whether or not the links were originally coarse-grained. "a" represents one of the original links. Note characteristic failure of one side of the link.

Many tests of this character have demonstrated that an exceptionally brittle link will break as indicated at "a" Fig. 94.

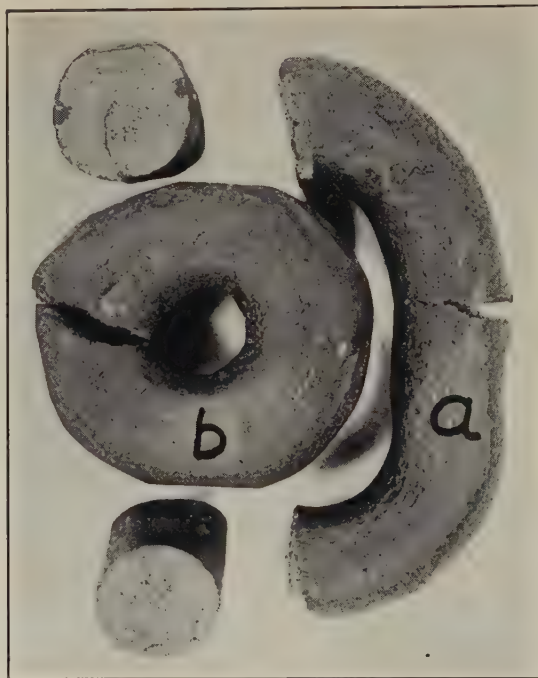


Fig. 95—Result of Annealing a Brittle Chain Link.

This, as you may notice, leaves one half of the link whole, provided failure occurs as above described. The fracture will show large shiny grains, self evidence that the entire link is coarse-grained. The sound half of the link was given a treatment similar to that given heat treated links "b" and "c". When cold it was bent under a power hammer to the form of a ring, as indicated at "b" Fig. 95. The results before and after treatment are clearly illustrated. Similar experiments were carried out on many types of bolts, machinery parts, and power tools, with such success that one firm installed an efficient heat treating equipment to treat materials.

## STRENGTH OF SLOWLY COOLED STEEL

It is a demonstrated fact that when steel is slowly cooled through the critical range as indicated in Fig. 78 such steel will be in its weakest possible state. To illustrate the strength of annealed steel Fig. 86 by Sauveur is shown. It illustrates four possible kinds or conditions of pearlite. The drawing is self explanatory and illustrates quite clearly the loss of strength as the areas of ferrite and pearlite increase in size. The massive grains are developed by high temperatures above the  $A_3$  and very slow cooling through the critical range. Maximum strength is developed by heating to just above the  $A_3$  critical temperature to develop fine structure and then cooling quite rapidly to below the lowest point of the critical range. The metal decreases in strength as the troostite or sorbite changes into pearlite. In hypoeutectoid steel the ferrite tends to form distinct and fairly large grains having a tensile strength of but about 40,000 pounds (20 tons) per square inch. Both pearlite and ferrite structures are weak; the first is brittle, and the latter very ductile. Slow cooling of hypereutectoid steel through the critical range causes the precipitation of massive cementite, resulting in a very brittle structure.

The size of these areas of pearlite containing ferrite and cementite, Fig. 86, depends upon the length of time the metal is held at elevated temperature and the speed at which the metal is cooled through the critical range. Large areas of varied pearlite are particularly noticeable in large sectioned castings or forgings that have been cooled slowly from high temperatures. By examination of diagram Fig. 78 it may be noticed that when any portion of the metal cools through the lowest point of the  $A_1$  critical range the austenite changes into pearlite. This change in plain carbon steel occurs about 1290 degrees Fahr. Continued cooling below the  $A_1$  does not effect further rearrangement of the crystalline structure, particularly in slow cooled steels. The question then arises "why" some specifications require the complete cooling of mass to atmospheric temperature with the danger of causing surface cracks if the metal is to be again reheated for further treatment. Why remove at least 1200 degrees of heat at some considerable cost in time and reheat by applying 1200 degrees of heat to the cold mass with the possibility of causing microscopic internal rupture?

It is fairly well understood that the rapid heating of cast iron, high carbon and alloy steel is dangerous practice because of the following: When there is a temperature difference of 250 degrees Fahr. between the heated surface and the adjacent cold section it sets up a fiber stress of 50,000 pounds per square inch. This is probably the chief reason for the rigid specification in the

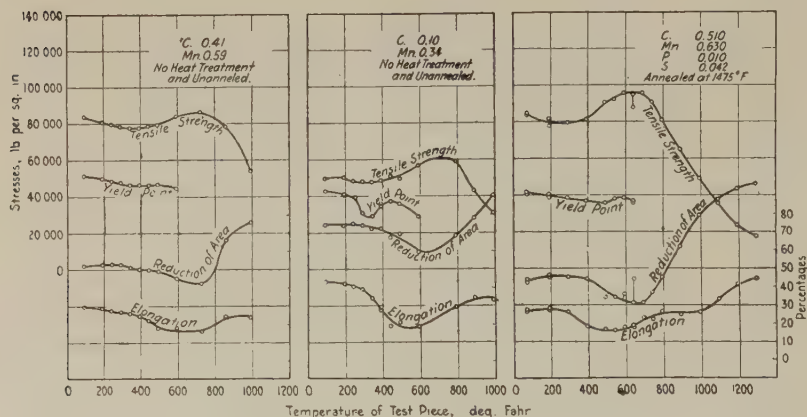


Fig. 96—Physical Properties at High Temperatures of 1-Inch Round, Rolled Open-Hearth Steel.—Courtesy of MacPherran.

rolling of steel rails, which says when, if mill trouble arises and it becomes necessary to allow the surplus ingots to cool to atmospheric temperature "such ingots must not be reheated and rolled into rails" because of the usual practice of heating the surface of such mass too rapidly and probably causing microscopic rupture to the inner portion. Rupture may be greatly aggravated in the rolling operation.

### *Strength of Metal at Elevated Temperatures*

In reheating for purposes such as forging, annealing, normalizing or hardening the following information should be given serious consideration. It is a known fact that metals have a definite strength at atmospheric temperature depending of course upon chemical analysis, the methods of fabrication and treatment. A prevalent opinion among metal workers holds that when heat is applied to metal it becomes weak in proportion with increase of temperature. Investigation by many well known engineers and

the Bureau of Standards has proven the reverse up to a certain temperature, from which temperature the strength of the metal decreases with further increase of temperature.

R. S. MacPherran, chief chemist of the Allis-Chalmers Company, Milwaukee, investigated the strength of metal at elevated temperatures to determine the most efficient kind of metal for internal combustion engines. The data collected in that investigation as well as many other similar lines of investigation might well be studied and applied. By referring to the three curves in Fig. 96 (MacPherran) it may be noticed that a straight 0.41 per cent carbon steel has a tensile strength of about 82,000 pounds per square inch at atmospheric temperature. By following the temperature ordinate it may be noticed at 400 degrees Fahr. that a slight drop in strength appears, but at 650 degrees Fahr. the strength again increases to about 83,000 pounds per square inch. On further heating of this type of steel the strength drops rapidly.

In the 0.10 per cent carbon steel curve at C it may be noticed that at atmospheric temperature such steel has the low tensile strength of about 45,000 pounds per square inch. At increasing temperatures, the strength remains about the same up to 400 degree Fahr. above which the strength increases quite rapidly. At 700 degrees Fahr. the strength is 60,000 pounds per square inch, a gain of about 15,000 pounds. In other words such metal is 15,000 pounds stronger at a temperature of 700 degrees Fahr. than at room temperature.

The curve of a 0.51 per cent carbon steel, indicated at the right of Fig. 96, shows a tensile strength of 82,000 pounds per square inch at atmospheric temperature. There is a slight loss of about 2,000 pounds at 300 degrees Fahr. but a rapid increase of strength to 98,000 pounds at 650 degrees Fahr., an increase of strength of about 16,000 pounds above its strength in the cold state. Upon further heating, the strength decreases rapidly.

### *Danger of Rapid Heating*

The reader may wonder what these facts have to do with the heating of steel. A few examples will convince the most skeptical. Records of tool, jig and die performance have proven that after second annealing, machining, hardening, and tempering, the output or service was much below the original service of a new tool.

The usual custom in annealing is to slip a hardened tool into a high temperature furnace or otherwise, to soften for machining. It is not at all unusual to find that one needs this annealed tool the day before it was ordered. Let us imagine the tool to be a die about the size of a book. When thrown on the bottom of a hot furnace, the die would immediately begin absorbing heat, the top of the die heating faster than the bottom. If this is doubted, change its location in the furnace or turn it upside down and note the black spot in the bottom of the furnace. The underside of the die will be much darker than the top. The heat could not circulate around the die.

It is a fact that when heat is applied to solids, they expand. In steel the expansion is about 0.000007 inches per degree Fahr. Imagine the surface of this hardened steel die extending in length with the strength increasing as it is heated up to 650 degrees Fahr. What of the hard and brittle, cold portion attempting to resist the expansion of the strong surface metal? Try pulling such hard, brittle material in a tensile testing machine and note the sudden rupture. Is it not possible that the extension of the strong surface metal may cause small internal ruptures that will not be noticeable in the machining operation? These small ruptures may withstand drastic abuse in hardening but when put into service the die may crack or fail.

In large masses of metal the structure of the center is not the same as the structure of the outer layers, therefore is it not conceivable that the expansion of the strong surface metal may cause internal ruptures, particularly in castings? If one desires to prevent such a defect it is a simple matter to heat *slowly and uniformly* for the first 800 degrees Fahr. at least. The danger of initial heating to 800 degrees Fahr. multiplies as the density, fineness of grain and hardness of the material increase and may be likened to the reheating of a cube of solid glass. If heated or cooled rapidly, the glass cube breaks into bits. Therefore, initial heating of hard and brittle material should be *slow and uniform* to at least 800 degrees Fahr.

In steel castings where specifications require annealing, why not remove the casting from sand and air cool to about 1200 degrees Fahr., cut off sprues, etc., repair all defects while the casting or mass is still hot, and avoid the danger of starting surface rup-

ture by uneven heating in annealing? Then take advantage of the heat remaining in such mass by placing it in the annealing furnace and immediately reheating for the purpose required.

### *Cooling of Large Carburized Sections in Pot*

The temperature required to carburize large masses is about 1700 to 1800 degrees Fahr. and for a considerable length of time. This temperature causes large grain growth in both core and case. On the other hand the part may require a grinding finish which means the possible removal of 0.20 of an inch of metal. It would be necessary to develop a rich carbon surface above the eutectoid composition, otherwise in the removing of 0.20 inches from the eutectoid case (0.90 per cent carbon) the remaining metal would not develop sufficient hardness, due to lack of carbon on the surface of the finished part. The usual custom is to allow such a mass to cool in the pot to atmospheric temperature and double heat treat to refine the core and case.

A study of Fig. 78 shows the forms which the constituents take when slowly cooled, and the change in structure at the  $Ar_1$  point, the separation of the free ferrite and cementite. Fig. 89 shows a precipitated network of cementite caused by slow cooling. What advantage is to be gained by allowing free cementite to develop in the case or free ferrite in the core, and why remove 1200 degrees of heat from below the  $Ar_1$  point unless for production purposes? Removing from the pot and air cooling or time quenching from the carburizing temperature to below the  $Ar_1$  point will keep the ferrite and cementite in solution. Why not utilize the remaining energy by immediately heating above the  $Ac_1$  point and quenching, to produce maximum hardness of the case? The free cementite in the case is held in solution by time quenching through the critical range, producing a moderately strong but large grained core. Time quenching prevents the formation of free ferrite in the core.

These points illustrate the possible ways of conserving energy and the reduction of surface and internal rupture. It is hoped that the reader may find time to study constitutional changes that take place as indicated in the drawing, Fig. 78, and that he may carry out simple experiments to fix these points in his mind.

## NORMALIZING

In a set of definitions recently promulgated by the American Society for Steel Treating and several other technical societies, normalizing is given as a form of annealing by the definition, "Heating iron-base alloys above the critical temperature range followed by cooling to below that range in still air at ordinary temperature." A note under the definition says—"In the case of hypereutectoid steel, it is often desirable to heat above the  $A_{cm}$  line." We have seen that massive ferrite and cementite form by

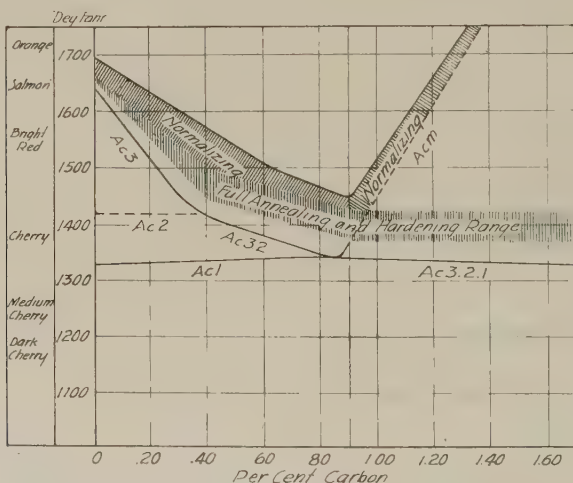


Fig. 97.—Iron-Carbon Diagram Showing Usual Annealing and Normalizing Temperatures.

slowly cooling steel through the critical ranges, and that this structure (Fig. 89 for a hypereutectoid steel) is quite weak. Further, if hypoeutectoid steel is heated to well above the  $A_{c3}$  range, the massive or free ferrite will pass fairly rapidly into solution as austenite; and if hypereutectoid steel is heated above the  $A_{cm}$  temperature, the massive or free cementite will pass fairly rapidly into solution, but the solution of ferrite and cementite is accompanied by grain growth.

The usual object of normalizing is to throw all microconstituents into solution. Rapid cooling as in air, or quenching in oil or water for smaller objects, prevents the reprecipitation of

ferrite or cementite in the massive form. They are either retained at room temperature in solution, or they are evenly precipitated through the mass in a very finely divided state. The large grains that form during normalizing may be broken up by annealing at just above the  $A_{c3}$ , followed by slow cooling if desired. Annealing will not seriously interfere with the normalizing treatment provided the temperature is closely maintained and not for too long a time. Fig. 97 shows the usual normalizing and annealing temperatures.

### GRAPHITIZING WHITE CAST IRON

Malleable cast iron is made by annealing or graphitizing hard white iron to precipitate the graphite. The white iron may be melted from pig iron and scrap in either a cupola or an air furnace. The analysis of the hard iron is about as follows:

	Per Cent
Silicon .....	0.50 to 1.25
Manganese .....	0.20 to 0.40
Phosphorus .....	under 0.225
Sulphur .....	0.04 to 0.10
Total Carbon .....	about 2.00 to 3.00

All carbon is retained in solution by properly proportioning the manganese, silicon and carbon. In annealing, the carbon is precipitated as far as possible. The analysis of annealed malleable iron is about the same as the white iron, except that only 0.20 to 0.50 per cent of carbon remains combined with the iron as pearlite. Fig. 91 shows the structures of malleable iron. Fig. 91A is a white iron, composed almost entirely of hard and brittle cementite. Fig. 91B shows the fully annealed iron. The graphite or "temper carbon" has precipitated in shapeless black blotches. The ground mass is ferrite plus pearlite. The amount of pearlite depends entirely on the amount of remaining combined carbon, so the groundmass may be regarded as a low carbon steel containing the amorphous carbon in shapeless, irregular blotches. Most malleable iron has a tensile strength of 50,000 pounds or more per square inch, and an elongation in two inches of about 15 per cent.

The annealing operation requires a total time of from 60 to 75 hours. The white iron castings are packed in annealing boxes filled with mill scale. The thermal cycle consists of heating to 1600 to 1650 degrees Fahr., extremely slow cooling through the  $A_{r1}$ ,

and faster cooling to room temperature. At 1600 to 1650, the carbon is precipitated out of the cementite, with the aid of a limited amount of the silicon. The temperature is dropped very slowly through the critical ranges to insure further precipitation of the carbon. The iron-carbon diagram shows that carbon is precipitated much more rapidly at 1800 or 1850 degrees Fahr. and the grains of ferrite grow very rapidly at the same temperatures. Much experimental work is being done, seeking to strike a balance between a faster rate of carbon precipitation and marked grain growth. Several hours could seemingly be cut from the long annealing periods. Possibly some more rapid annealing practice will soon be evolved.

### SCALE

By reheating finished parts or fine tools in an oxidizing atmosphere a thick coating of scale or oxide of iron is formed on the surface of the material. This is undesirable. It is difficult to prevent where the fuel and air supply are not closely regulated. The formation of scale is due primarily to an excess of air in the mixture. In olden times when we had bellows or hand blowers to pump air, there was usually little excess, but today with our modern power blowers, men often use too much air. As one old chap said, he likes to see a nice sharp flame coming out of the furnace hearth. It is that sharp flame that creates oxidation and scaling.

Iron has a great affinity for oxygen and any excess of oxygen in the furnace above that necessary for perfect combustion is attracted by the iron, forming scale in proportion to temperature and the amount of free oxygen present. One may easily demonstrate the conditions. When a furnace and charge are red hot, throw in a large piece of coke or charcoal. When this is red hot and the combustion gases neutral, the coke, the charge and walls of the furnace will be the same color. If the atmosphere is oxidizing, the piece of coke will become incandescent and therefore considerably brighter than the charge of the furnace walls. This is a clear indication of an oxidizing atmosphere. Next, reduce the air supply until the coke, charge, walls, and material are the same temperature. The atmosphere is again neutral, or reducing. To

be sure of the atmosphere, determine the proper air and fuel adjustment to make it just oxidizing, then cut down the air supply slightly, and a definitely reducing atmosphere will result. Unfortunately a reducing atmosphere slows up production, but if one desires to have a clean piece of work after annealing or hardening, the writer would advise this simple check to prevent excessive scaling.

## LECTURE IV

### DETERMINATION OF CRITICAL POINTS AND PHYSICAL TESTING

In the third lecture we discussed the thermal critical points of the iron-carbon diagram and the principle microconstituents and saw their application to annealing and cooling processes in general. But these points are of no great value unless we can determine them for ourselves. The microstructures, as stated, were included by the author in order that the reader might have a clear means of visualizing the structural changes that take place as steel is heated and cooled, and also to enable the reader to recognize the simpler structures that he will encounter when reading the literature on this subject. This lecture defines the temperature scales in common use, and shows some of the usual methods of measuring the elevated temperatures encountered in treating steel, and gives practical means of determining the critical points. A section shows what "tensile strength" means, and how it is determined, also methods of hardness testing and other physical measurement are given.

#### *Temperature Scale*

The ordinary house thermometer scale is graduated between two points, the freezing point of pure water and its boiling point. The Fahrenheit scale, in common use in America and England, arbitrarily sets 32 degrees above zero as the freezing point of water, and 212 degrees above zero as the boiling point of water. This interval is divided into 180 equal divisions. The Centigrade scale, in general use in Europe and for scientific work, sets the freezing point of water at zero (0), and the boiling of water at 100. The interval is divided into 100 equal parts. Since much of the literature regarding the treatment of steel records temperature in terms of the Centigrade scale, it is convenient to have a conversion table at hand. Fig. 98 shows both temperature scales, up to very high temperature ranges. A simple formula will enable us to convert temperatures without the aid of a conversion chart. The interval between the freezing and boiling points of water is 180 degrees by the Fahrenheit or 100 degrees by the Centigrade scale, therefore:

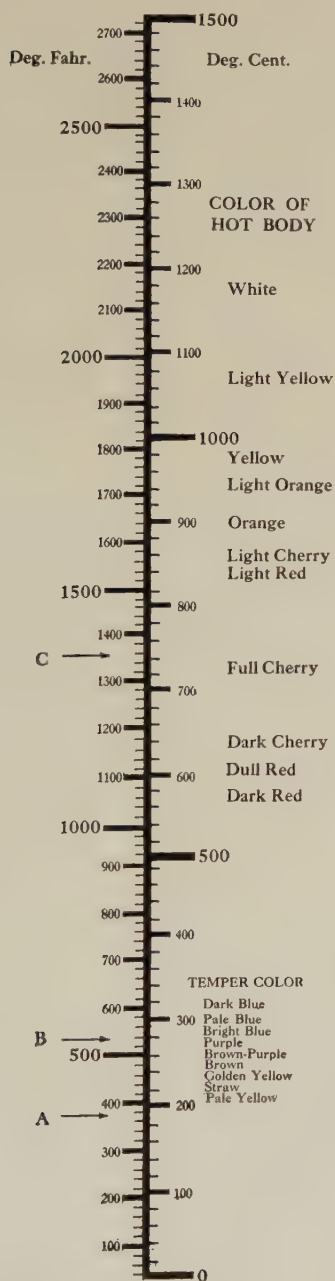


Fig. 98 Temperature Conversion Chart.

$$\frac{1 \text{ degree Cent.}}{1 \text{ degree Fahr.}} = \frac{100}{180} = \frac{5}{9}$$

But zero Fahrenheit is 32 degrees below the freezing of water, hence the 32 degrees must be taken into account to reach the Fahrenheit zero. Let us convert 104 degrees Fahr. into degrees Centigrade.

$$104 - 32 = 72 \text{ (to adjust from zero to the freezing point of water which is the starting point in converting temperatures)}$$

$$72 \times \frac{5}{9} \text{ (equivalent of 1 degree Cent.)} = 40 \text{ degrees Cent.}$$

Let us convert 485 degrees Cent. into degrees Fahr.

$$485 \times \frac{9}{5} \text{ (equivalent of 1 degree Fahr.)} = 873$$

But this is just temperature Fahr. above the freezing of water, 32 degrees Fahr., so it must be adjusted to the Fahr. zero.

$$873 + 32 = 905 \text{ degrees Fahr., the equivalent temperature.}$$

Elevated temperature intervals are the same as between the freezing and boiling points of water. That is, the interval 1291 degrees Fahr. minus 1290 degrees Fahr., is the same as 105 degrees Fahr. minus 104 degrees Fahr., an interval of one degree at any place in either scale is always the same.

## HIGH TEMPERATURE MEASURING DEVICES

### *Thermoelectric Pyrometer*

The most generally used device for measuring the temperature of a heat treating furnace is a "thermoelectric pyrometer system" consisting of a "thermocouple" at the furnace connected by wires to a temperature measuring instrument, either an indicating or recording instrument or both. Fig. 99 shows a diagrammatic sketch of a pyrometer system.

The thermocouple is made of two physically dissimilar wires shown at A and B, twisted together and welded at one end of the couple, the end placed inside the furnace called the "hot junction." The couple should be encased in a protecting tube. The other end, remaining outside the furnace, should be kept at a constant or fixed temperature and is called the "cold end." By connecting the cold end of the thermocouple to a galvanometer or millivoltmeter (marked instrument in the sketch), an electric voltmeter that is so

sensitive it reads in thousandths of a volt, the difference in temperature between the hot and cold ends of the couple generates an electric current. The strength of current is proportional to the difference in temperature between the hot and cold ends, so the instrument is usually calibrated in degrees Fahrenheit or Centigrade instead of in electrical units. Metal combinations for thermocouple wires have been carefully worked out by the manufacturers. In general, the lower priced iron, nickel, or chromium combinations are useful up to 2000 degrees Fahr., and the very expensive plati-

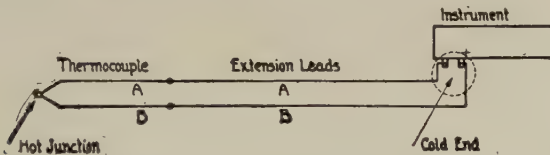


Fig. 99—Diagrammatic Sketch of a Thermoelectric Pyrometer. A and B to the Left are the Thermocouple Wires. A and B at the Center are Extension Leads to the Cold End Which is Kept at Constant Temperature. The Instrument Can be an Indicator, Potentiometer, Recording Instrument, Galvanometer, Etc.

num and rare metal combinations are useful up to 3000 degrees Fahr. The instruments can be conveniently checked or recalibrated by determining the freezing points of a series of pure metals such as bismuth, aluminum and copper, then adjusting the instrument or plotting a curve from which the correct temperature can be read. Galvanometers, millivoltmeters, potentiometers and recorders are described at length in standard text books. The principles upon which they work, their advantages and disadvantages, are too complex for this more elementary discussion.

Fig. 100 shows a pyrometer used for controlling a heat treating furnace. The thermocouple is inserted through a hole in the door. Note the protecting tube that encloses the thermocouple and terminates in the binding posts to which the extension leads are attached. The extension leads run through conduit to the direct-reading indicator that the operator is reading, and to one of the recording instruments shown in Fig. 101. The indicator is for the guidance of the furnace operator in controlling his furnace fires, and the recording instrument gives a permanent record of the furnace operation.

### *Optical Pyrometers*

Thermocouples are useless for measuring temperatures above

3000 degrees Fahr. as the wires disintegrate or melt above this temperature. Optical instruments are available for measuring the higher temperatures. Fig. 102 shows one type of optical pyrometer. In general, they consist of a hand tube and a battery box containing a galvanometer. The hand tube looks much like an old fashioned spy glass, only it is shorter and contains a lens and an



Fig. 100—A Typical Thermoelectric Pyrometer Installation for Controlling a Heat Treating Furnace. Courtesy of Breen Instrument Co.

electric light bulb or color screen. At temperatures of 1500 degrees Fahr. and higher, the furnace, metal, etc., is distinctly luminous. The tube is sighted on the furnace wall, metal object, etc., and the color of the light filament or the color screen is matched to the color of the object whose temperature is being taken. The galvanometer in the battery box is affected by this adjustment, and the temperature is read on the instrument scale. Fig. 103 shows an optical pyrometer used in determining the temperature of an ingot that is to be forged.



Fig. 101—A Battery of Pyrometer Recording Instruments that make a Permanent Record of Furnace Operation.—*Courtesy of Brown Instrument Co.*

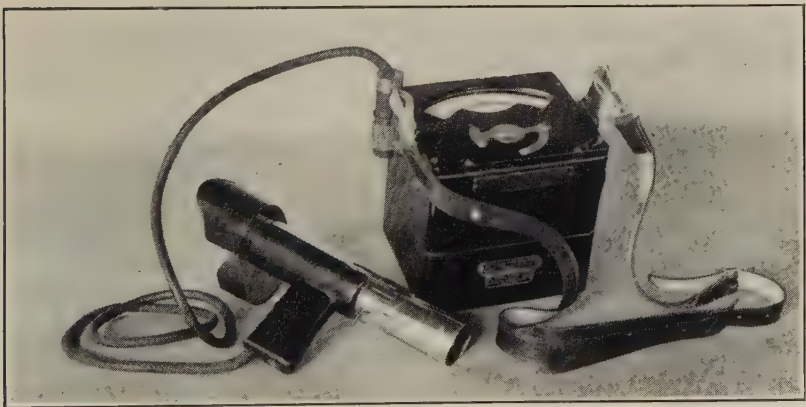


Fig. 102—An Optical Pyrometer.—*Courtesy of Leeds and Northrup Co.*

Detailed descriptions of high temperature measuring devices are given in standard textbooks. Many cautions, schemes for calibration, adjustment, etc., are given in the *HANDBOOK* of the American Society for Steel Treating.



Fig. 103—Using an Optical Pyrometer for Determining the Temperature of an Ingot About to be Forged.—*Courtesy of Leeds and Northrup Co.*

### *Determining Temperature by Eye*

In the olden times and even today, men had the peculiar idea that to harden or toughen a piece of steel it was only necessary to heat the steel (regardless of temperature) and quench it in water. If the desirable characteristics were not forthcoming in the first attempt it was simply a matter of heating to a higher temperature and quenching it more drastically. This was the writer's early conception as a mechanic.

Later on but still in the olden times, men sought to heat tool steel to a dark cherry red, hoping that the transformation would take place. Now cherries vary in color and it would not be desirable to carry a dark red cherry in one's pocket at all times. Again, light and health influence one's ability to judge colors. In determining the critical temperature by the eye it is preferable to use a moderately dark room where the light is nearly constant because any variation in light will change the apparent color of heated steel. A simple demonstration of this point is to observe a lighted lantern in sunlight and note the difference on a dark

night. The ideal hardening room in the author's estimation, even in procedure control, is one in which the light is constant 24 hours per day. The determination of the critical point by the eye has been questioned by men because it is something different from a cherry red heat. At the critical point a phenomenon takes place called "decalescence" or "recalescence" that is observable to the "trained eye" only under light conditions as above described.

Let us assume that the old gentleman observing the furnace temperature, Fig. 104, is heating for hardening a fair size blanking die about the size of a book. He is attempting to heat the die



Fig. 104—The Simplest Form of Pyrometer, the Human Eye.

to above its critical temperature. If the die (high carbon steel) is heated slowly and uniformly the heated portion will become hotter and of course brighter, and continue increasing in brightness until the  $A_1$  transformation point is reached, at which point a dark shadow (decalescence, darkening) appears on that portion of the steel passing through its transformation (changing from pearlite to austenite). When the change of state is completed the steel continues to increase in brightness. After this phenomenon has occurred the trained eye can only determine or guess at the temperature by color. Here again, light is an important factor. The great advantage of the trained eye is to determine if all the shadows have disappeared from the die thus indicating that the

transformation has been completed, throughout the whole die. In procedure controlled plants the time of heating above the critical temperature is fixed and pyrometers are used to determine these temperatures. When the shadows have all disappeared from the die, indicating completion of the transformation, the old gentleman must quench it quickly before the "recalcescence," (the change on slow cooling) or relighting, occurs in the die.

If one wishes to observe "decalcescence," select a piece of steel wire containing about 0.90 per cent carbon. In a dark room, con-

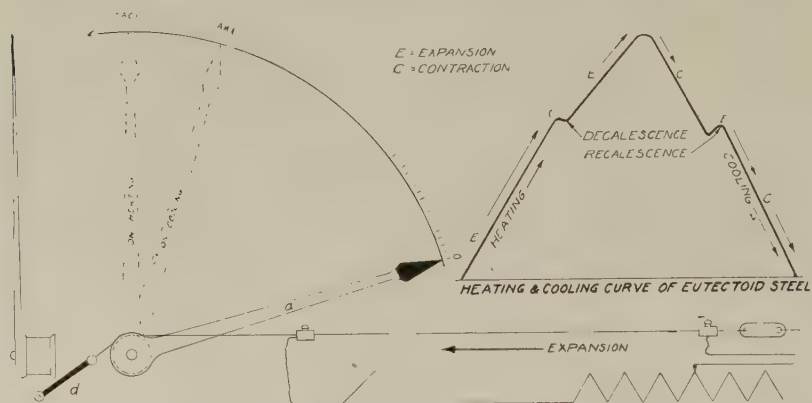


Fig. 105—Decalcescence and Recalcescence Points Illustrated by Heating a High Carbon Steel Wire. The Pointer Mechanism Magnifies the Expansion and Contraction That Take Place on Cooling and Heating.

nect between two poles and pass an electric current through it. Three important things will occur: (1) the wire will expand, (2) it will increase in brightness; and (3) when the transformation occurs the wire will darken and contract slightly during the change. On close observation one may note in a fairly high carbon steel wire of fine diameter, that the transformation is not instantaneous.

If we now allow the heated wire to cool from above the critical range, several things occur quickly. The wire darkens and contracts until it cools to the recalcescence point, at which the wire "relights" or recalcesces with considerable expansion. This phenomenon is due to the metal evolving the heat of the transformation change from austenite to pearlite. During this change the metal returns to its former state of soft steel, hence the necessity for rapid quenching before the change occurs, in order to retain hardness.

*Demonstration of Decalescence and Recalescence*

To emphasize and demonstrate these points the writer devised a device along the lines indicated in Fig. 105. It consists of a piece of 0.90 per cent carbon steel wire, electrical connections, a resistance coil, an arm on a fixed center, a piece of twine, a carpet tack and a rubber band connected at "d." Set "a" at zero. Before beginning operation there are several points to be considered.

- (1) The piano wire used originally had a strength of 350,000 pounds per square inch.
- (2) The wire expands upon the application of heat.
- (3) When passing through its critical transformation it has very little strength and due to this factor the wire elongates. As evidence of this point, the arm "a" or pointer will not return to zero when the wire returns to room temperature.
- (4) When the rising temperature of the wire reaches the transformation temperature, the pointer stops and, in fact, moves backward even though the electric current is continually heating the wire, evidence of a slight contraction while the  $Ac_{3-2-1}$  critical transformation is taking place. When the transformation is completed the wire continues to expand.
- (5) It is supposed by many that when steel cools it contracts at an even rate to atmospheric temperature, but this wire demonstrates the opposite. When the current is shut off, the wire cools quite rapidly at an even rate until it cools to 1290 degrees Fahr., the  $Ar_{3-2-1}$ , at which temperature a very pronounced expansion, "recalescence" takes place and is shown by the forward movement of the arm "a," about  $2\frac{1}{2}$  times the amount of expansion over that of contraction at the  $Ac_{3-2-1}$  point.
- (6) Every time the wire is heated above the  $Ac_{3-2-1}$  point and again allowed to cool to atmospheric temperature the wire elongates.
- (7) The reader will recall that the  $Ar$  (on cooling) transformation takes place at a lower temperature than the  $Ac$  (on heating) transformation. With the wire, the  $Ac$  transformation cannot occur until the  $Ar$  transfor-

mation of the previous cooling has been completed. In other words, if the wire is cooled to just above the Ar temperature and then reheated, no Ac transformation can take place. The Ac transformation will occur at each application of heat provided the Ar transformation has occurred, otherwise there will be no "kick back" or transformation.

We learn from this demonstration (1) that it is absolutely necessary for the Ar change to occur before we can expect the Ac reaction on subsequent reheating but; (2) it is not necessary to cool to atmospheric temperature but only to cool through the Ar before we can again create the Ac transformation, being sure the Ar change has occurred; and (3) a few seconds after the recalcence had occurred, the current can again be applied, and the Ac change will occur. This then should emphasize the point previously stressed, that it is not necessary to remove 1200 degrees of heat if the metal is to be again reheated for any purpose.

If a tool is allowed to cool down to the proper hardening temperature after being overheated at a higher temperature, quenching will not affect the large grain structure caused by overheating. It is not at all uncommon to overheat valuable tools. Such overheating will, of course, cause grain growth in proportion to the temperature above the  $A_3$  and the length of time at the high temperature. The fracture, Fig. 106 at the right of the point A, clearly illustrates what may happen. Many operators would allow an overheated piece to cool to the hardening temperature and then quench and try to get away with it. If the material or tool is inefficient or fails, the trouble is often blamed on the quality of the steel. The proper procedure is to allow the tools or charge to cool to just below the  $Ar_{3-2-1}$  point and then reheat. Upon reheating through the  $Ac_{3-2-1}$  point transformation again takes place and a new structure is again formed as indicated at the point A.

#### *Fracture Test for Determining the Critical Point*

A rough method of locating the critical temperature is by the fracture of a bar of steel. Select a piece of carbon steel about  $\frac{1}{2} \times 2$  inches and as long as the widest and strongest vise available. Make a sharp V-notch in the middle of the widest cross section,

and full length of the bar. Over anneal at well above the  $A_3$  temperature for some time and cool slowly in the furnace to develop large grain growth in the entire bar. When cooled below the  $Ar_{3-2-1}$  point or to atmospheric temperature, hold one end in a pair of tongs and heat the other end to a white heat, heating the balance in such a manner that the temperature will gradually diminish to

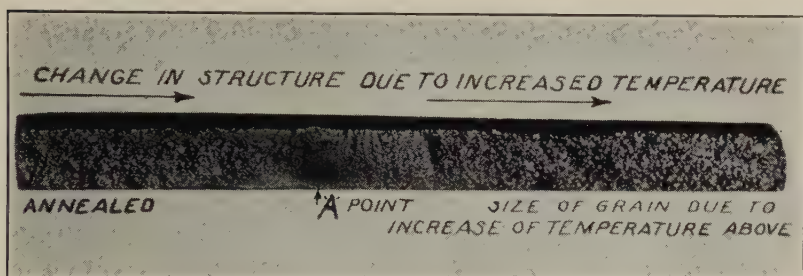


Fig. 106—Fracture of a Bar Showing the Result of Heating Steel to Below the  $A_1$  Critical (Shown to the Left of A), Proper Heating at the  $A_3$  Critical (Shown at A), and Overheating to Above the  $A_3$  Critical (Shown to Right of A).

a dark red about the center of the bar. Note about the position of this dark red for future information and quench the entire bar quickly in water. When cold, dry the bar, fasten it in the vise and break it along the notch. If carried out as suggested one will have fracture similar to Fig. 106. It will be found that the point A where grain size is finest was the portion of the bar attaining a dark red heat. Point A represents the critical temperature  $A_3$ . Preserve this for future reference.

#### *Fracture Method of Determining the Critical Temperature by Using a Pyrometer*

A more refined fracture test for determining the critical point in steel that will harden somewhat upon quenching and rupture easily when the sample is clamped in a vise and is struck with a hammer, is shown in Fig. 107.

In this test, it will be necessary to have a thermocouple and indicator. We wish to know at what temperature the transformation occurs in the particular type of steel under examination. Select a sample of the desired type of steel; cut it into lengths of about two inches, as indicated at "a," Fig. 107; nick each piece

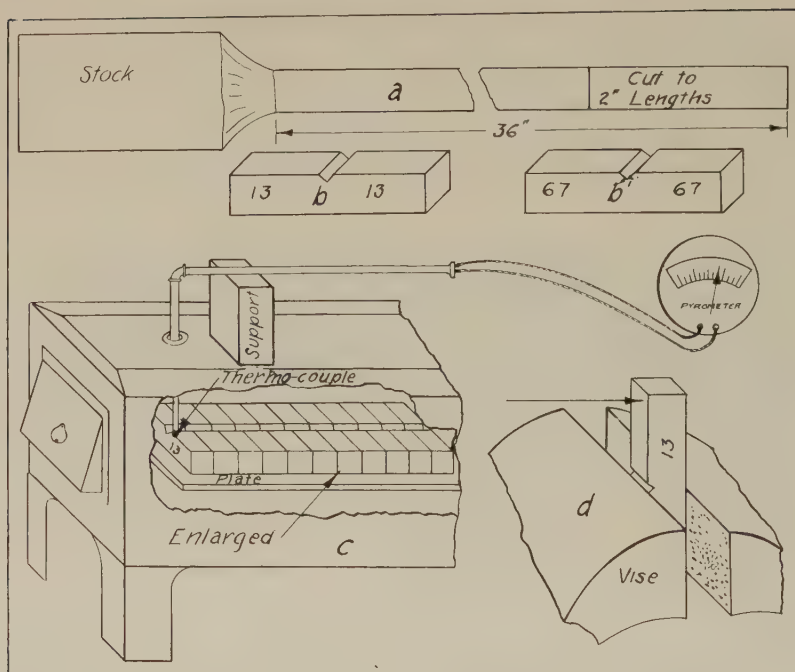


Fig. 107—A Refined Method of Determining the Critical Point of Steel by the Fracture Method.

with a chisel as indicated at "b," and number for identification. That these samples may be identified after treatment, it is important that the first one be marked to indicate a temperature below the lower end of the critical range. The first sample can be marked to indicate 1300 degrees Fahr., the next one 1325 degrees Fahr. and continuing on at twenty-five (25) degree intervals until the last sample is marked at about 1675 to 1700 degrees Fahr. In marking these samples for identification the writer offers the following scheme of abbreviation: 13 = 1300 degrees Fahr., 32 = 1325, 35 = 1350, 37 = 1375 and continue in that order to the end as indicated at "b'" where 67 = 1675 degrees Fahr.

The next step is to place these samples on a plate of iron with the one marked the lowest temperature, 1300, in front of the plate and close to the front of the furnace door. The remaining samples are placed in regular sequence so that the highest number will be at the back end of the plate. Place the plate in a furnace in

such a manner that the front end of the pile will be directly under the thermocouple and arrange the couple so that it will be in direct contact with sample number 13 on the plate as indicated at "c." Regulate the furnace temperature so the samples do not heat too rapidly. When sample 13 reaches 1300 degrees Fahr. as indicated by the pyrometer, remove and quench it quickly in water, moving the entire line of pieces forward so that the next one will be in contact with the thermocouple. When it reaches its temperature, quench likewise and so on through the test. Remove the samples from the quenching tank, place in a bucket of water and heat the contents of the bucket over a gas flame, forge fire, or otherwise until the water boils for two or three minutes. Pour out the water and scatter the samples on a board or dry bench. This operation removes moisture from the sample. When the samples are cold enough to handle, proceed as follows:

Place sample 13 in a vise with the nicked portion toward the operator and just at the edge of the vise as indicated in "d." Then hit the tool a sharp blow with the hammer. Care should be taken, to have a gunny sack or some clean receptacle to catch the sample and prevent soiling the fracture. Warning! Under no circumstances attempt to hit the piece of steel with the face of the hammer as you may lose an eye. Also note carefully the amount of force necessary to rupture each sample. The natural tendency will be for each individual to be careless in handling the samples as it is human nature to want to feel the surface regardless of the condition of one's fingers. Be sure your fingers are dry.

Prepare a display board for inserting these small samples in the order in which they came out of the furnace, as indicated in Fig. 108. Upon examination it will be found that one or two of these samples are exceptionally fine and dense grained, indicating that they were quenched from the critical temperature. These samples will indicate the temperature of the critical point according to the instrument used and should the instrument be somewhat off calibration, it makes no difference as the indicated temperature will be used, regardless of correct calibration. If furnace capacity is available one may run five different steels in the same heat arranging the samples in five parallel rows. If one wants a closer check, a few more samples may be tried out within the range of the critical temperature indicated by the test and at closer tem-

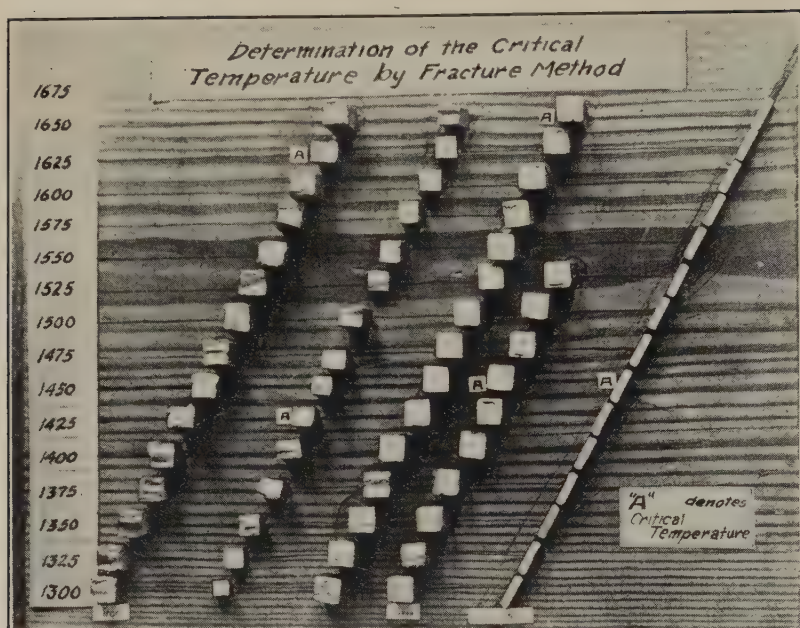


Fig. 108—Comparison of Fractured Samples by Arrangement on a Display Board.

perature intervals than 25 degrees.

This type of test has several advantages. In particular, it furnishes the operator and those having control, a picture of just what takes place at the different temperatures and the exact temperature necessary to secure the desired results. A check of this character will keep men posted upon the effect of the treatment given the metal. It also arouses the personal interest in the operator to investigate other types of steel.

### *The Critical Point Determined Magnetically*

Iron and steel become nonmagnetic when heated through the  $A_c$  critical range, and become magnetic again when cooled through the  $A_r$  critical range. Up to the  $A_2$  temperature, the metal being heated will be attracted by a magnet, and above that temperature such magnetic attraction will no longer be possible. This is possible in steel containing about 0.50 per cent carbon, or higher. For steels lower than 0.50 in carbon, attraction is too weak to give

a reliable magnetic indication of the  $A_2$  critical range. Further, for steels containing 0.50 per cent or more carbon, the  $A_2$  point is merged with the  $A_3$  as the  $A_{3-2}$  or  $A_{3-2-1}$ .

Such a magnet is shown in Fig. 109. The pin through the magnet bar and brass rod should fit loosely to allow the magnet to move freely. If held near a magnetic piece of steel, the magnet will deflect to make contact with the steel. When the surface

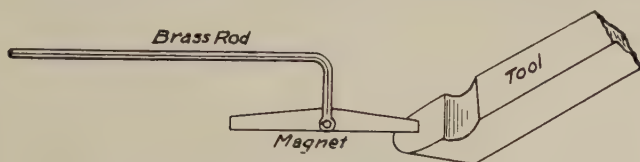


Fig. 109—Magnet for Determining the Critical Point of Steel Magnetically.

layers of the steel become nonmagnetic the magnet will promptly swing to the horizontal position. Fig. 110 shows such a bar magnet being applied to a reamer that is being heated for hardening. This looks simple on its face but the magnet must be applied

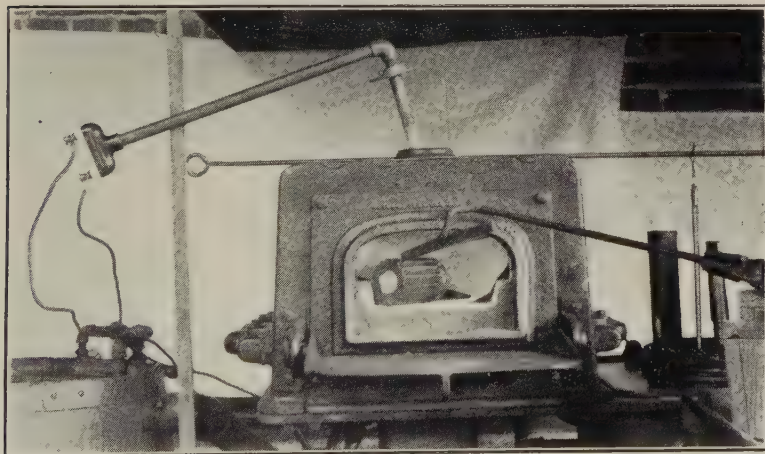


Fig. 110—Setup for Magnetic Determination of the Critical Point.

intelligently. The surface of the mass of steel always attains heat first. When the transformation takes place, the surface of the metal becomes nonmagnetic regardless of interior con-

ditions; consequently the magnet is of no value in determining the complete transformation of the whole mass, but the magnet is a wonderfully simple tool with which to determine when the transformation is completed on the surface. By holding the steel at the indicated temperature for a given time depending upon the mass, it is a wonderful improvement over the trained eye. The magnet may be used to roughly check the pyrometer.

The fracture shown in Fig. 111 shows an experiment carried out by the writer to demonstrate these points. A  $1\frac{3}{4}$ -inch piece of tool steel was heated in a cylindrical furnace for a few minutes

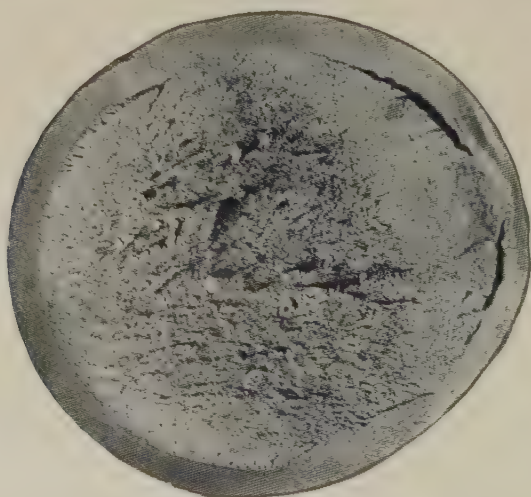


Fig. 111--Showing a Bar of Steel That Was Not Properly Soaked at Hardening Temperature Before Quenching. Only the Outer Portion is Hardened, Shown as a Definite Ring Surrounding the Bar.

after the surface became nonmagnetic and was then quenched rapidly in a salt solution. We learn from this the advantage of soaking the tool or sample until the whole mass attains the proper temperature. The fine structure at the outside is the only portion that reached the correct hardening temperature. The distinct line of demarcation shows that hardness cannot take place unless transformation takes place throughout the entire mass. The surface ring of hard fine-grained metal is evidence of complete transformation only at that zone. This picture illustrates one of the chief reasons why the magnet has not been used successfully.

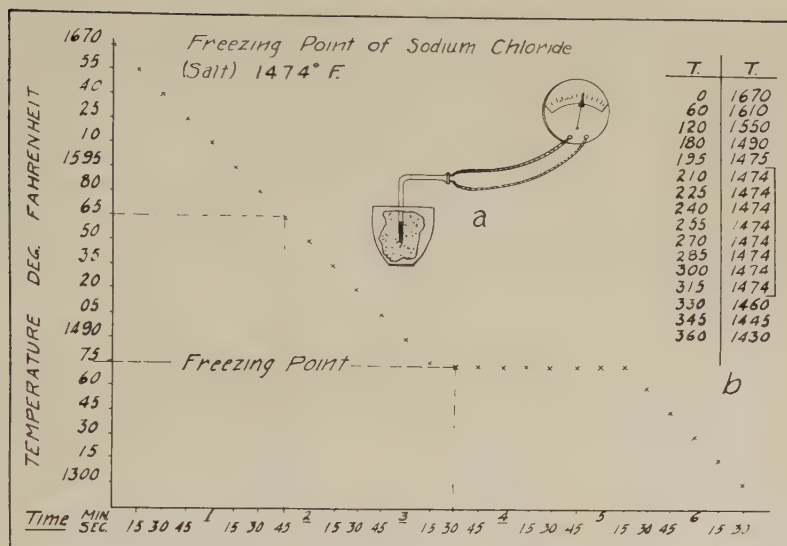


Fig. 112—Illustrating the Determination of the Freezing Point of Sodium Chloride (Salt) by a Pyrometer.

A further study of this fracture will not be out of place. Let us assume that the steel has been removed from the furnace a few moments after completion of the transformation at the surface only. As indicated by the magnet, it is very probable that recalcence would have occurred before the steel reached the quenching bath, therefore no hardness. Such results would be due to the cold interior absorbing the surface heat, since prolonged time of cooling from 1400 degrees Fahr. to 1290 degrees Fahr. would cause the steel to recalcence and return to its usual soft state. This shows why it is impossible to harden a 1-inch diameter piece of steel through to its center, unless the steel is heated somewhat above the decalescence point. Even with drastic quenching the very center would recalcence before the heat could be removed from the center of the mass.

#### *Determination of the Critical Temperatures by Using the Pyrometer*

To determine the critical temperatures by the pyrometer requires a very sensitive millivoltmeter and thermocouple. In order

that the reader may have a better conception of how to perform this operation, the manner of determining the freezing point of salt (sodium chloride) is inserted to simplify the discussion.

Select a clean crucible and fill it with chemically pure sodium chloride (salt). If not available use common table salt, but it may cause a variation of a few degrees owing to its impurities. Place the crucible on a forge or other fire and melt the salt, heating it to about 1650 degrees Fahr. Remove from the fire and insert the thermocouple as indicated at "a," Fig. 112. Record the tem-

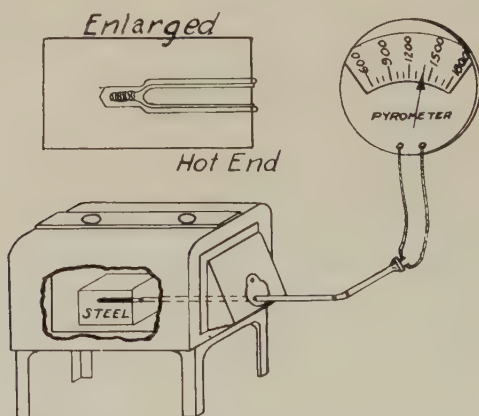


Fig. 113--Determining the Critical Point of Steel by Using the Pyrometer.

perature of the salt at 15 second intervals, as shown in data table "b." From these data plot cooling curve as indicated by small marks "x." When the salt freezes the temperature remains constant for a time at 1474 degrees Fahr. This method is also used to calibrate thermocouples.

Now drill a hole of sufficient size in a small block of steel or iron to insert the hot end of the thermocouple. Insert the thermocouple in the block and place in a furnace as indicated in Fig. 113. Heat the block to about 1750 degrees Fahr. and take time-temperature readings, similar to that of the freezing point of salt, by allowing the furnace and the block to cool slowly. While passing through the critical temperature, the temperature of the steel block remains fixed for a few seconds. At each critical point the curve shows a horizontal line as did the salt when it froze.

Typical curves are shown in Figs. 114 and 115. From these curves, Fig. 115, the portions of the iron-carbon diagram at the left side were drawn. As the carbon content increases, the  $Ar_3$  temperatures become lower and lower, until it merges with the  $Ar_2$  and finally with the  $Ar_1$  in steel containing 0.90 per cent carbon, the eutectoid composition. Fig. 116 shows heating curves, and the  $Ac$  critical points on heating.

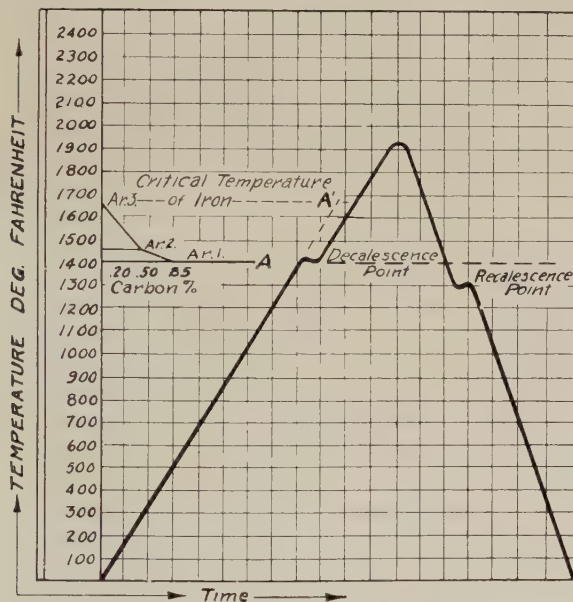


Fig. 114—Time-Temperature Curve on Heating and Cooling a Small Block of Steel, Showing the Thermal Critical Points of a Steel Containing 0.90 Per Cent Carbon.

As we have seen, the recalescence points (the Ar transformations) on cooling take place at a lower temperature than the decalescence points (Ac transformations) on heating. Fig. 114 shows this quite clearly in the heating and cooling curve of a 0.90 (eutectoid) per cent carbon steel. Fig. 115 shows cooling curves for several steels, and the iron-carbon diagram formed by joining these temperatures together by a smooth curve. Fig. 116 shows the same thing on heating. Comparison of the Ar and Ac points in Figs. 115 and 116 shows the variations between the Ar and Ac temperatures.

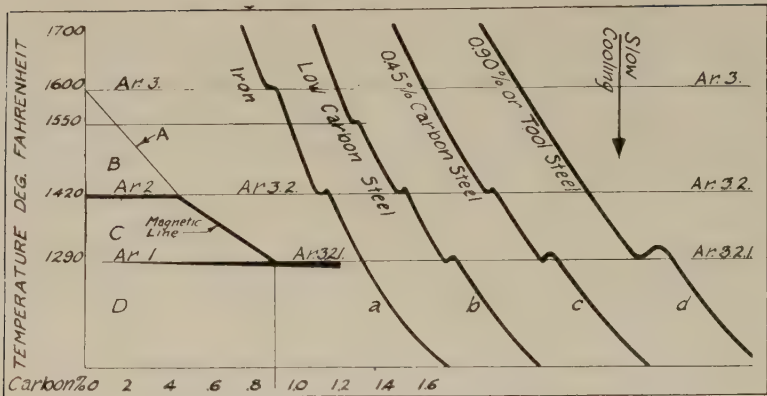


Fig. 115—Selected Cooling Curves of Steels, Showing the Ar Thermal Critical Points.

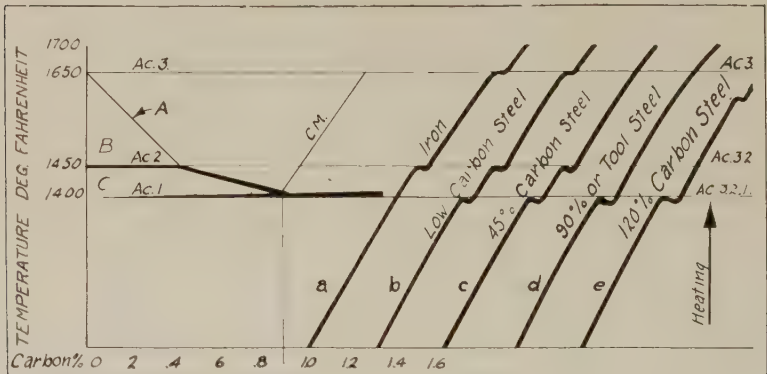


Fig. 116—Selected Heating Curves of Steels, Showing the Ac Thermal Critical Points.

The determination of the critical points by the thermoelectric pyrometer requires very sensitive laboratory equipment. It cannot be used in the average shop, and is inserted here only to show how these determinations are accurately performed.

#### *Determining Critical Points on Tools in Production Instead of Laboratory Samples*

The foregoing methods of determining the critical points show that it requires an appreciable time for steel to pass through a critical temperature. When steel is heated through the  $A_3$  critical

point, the darkening of the steel at this temperature, the temperature lag of the steel itself as indicated pyrometrically by taking the temperature at a point inside the piece of steel and the fact that the steel undergoes a dimensional change at these points are all evidence that an appreciable time is required for the complete change (pearlite to austenite) to take place. The methods of determining this point thus far given have required the determination of the  $A_3$  point to be made in the laboratory or shop with samples

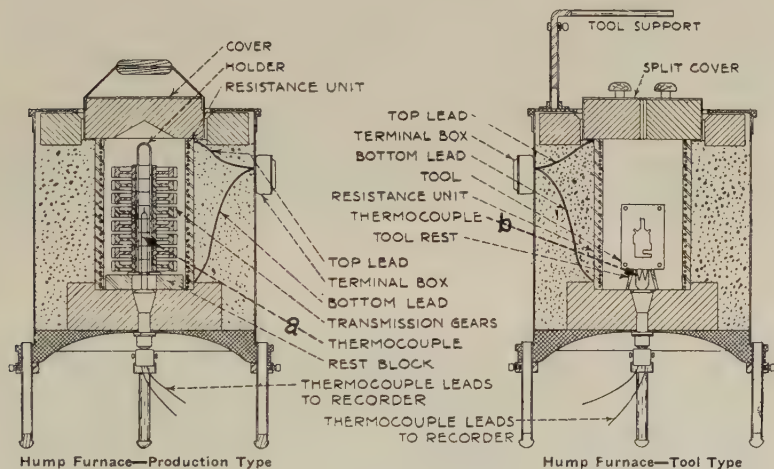


Fig. 117—Cross Sectional View of a Hump Heat Treating Furnace.—Courtesy of Leeds and Northrup Co.

of the steel and not on work in actual production. Would it not be a great aid to fine work if these determinations could be made on each piece while being heated through the  $A_3$  temperature, the point above which the steel is quenched for hardening (to retain austenite or martensite)? This would do away with predetermining this temperature. Variations in analysis would be automatically taken into account and the human element discarded. Proper quenching temperature and heat penetration would be certain of control.

This is possible for small parts such as automobile gears and tools by at least two quite generally used production methods. One plots a time-temperature curve of the steel from a thermocouple inserted in the work being treated. The  $A_3$  temperature is shown by the lag of the curve at this temperature, while the pearlite

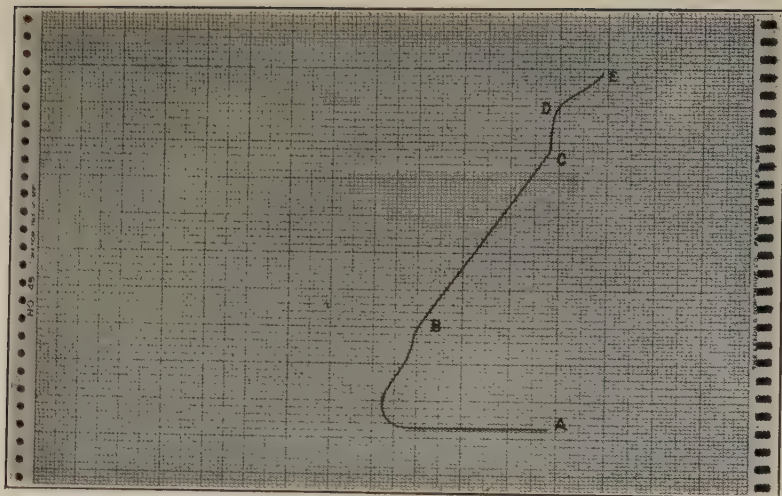


Fig. 118—Heating Curve of a Hump Heat Treating Furnace.



Fig. 119—A Battery of Hump Heat Treating Furnaces.—Courtesy of Leeds and Northrup Co.

to austenite transformation is taking place. The other measures the expansion and contraction of the steel. By means of a lever system the dimensional changes are greatly magnified. A chart is plotted by a pen. At the  $A_3$  point there is an actual contraction which clearly shows on the chart, indicating when the transformation is complete.

### *Hump Method of Heat Treatment*

A "hump" furnace is shown in Fig. 117. The charge in this case is eight automobile transmission gears which are being tough-

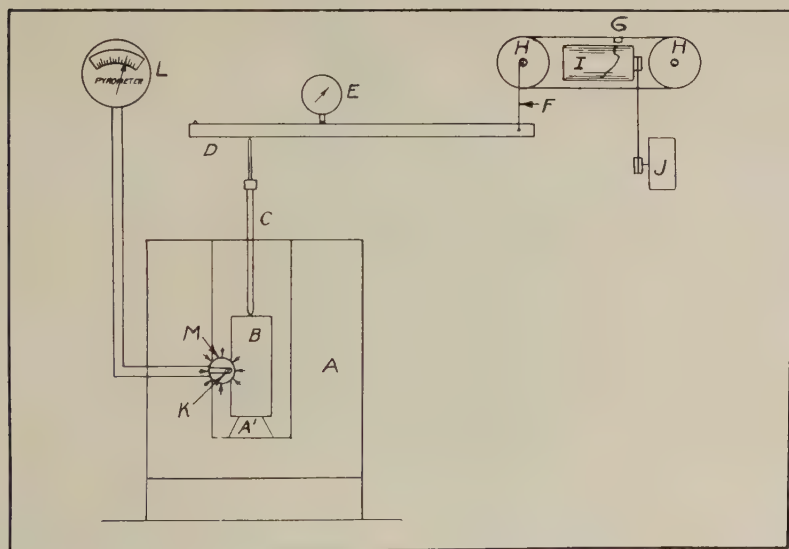


Fig. 120—Schematic Diagram of a Dilatometric Heat Treating Furnace.

ened. A thermocouple "a" is placed inside and in close contact with the gears; so it will indicate the temperature of the gears rather than the temperature of the furnace atmosphere. A tool furnace shows a similar set-up with couple "b" in contact with a tool that is being hardened. Fig. 118 shows a typical temperature curve. Vertical lines represent time, and horizontal lines represent temperature. At A the cold charge has been placed in the furnace. The hump at B is caused by the  $Ar_1$  transformation. C is the start in temperature lag of the  $Ar_3$  transformation. At D the

transformation is nearly completed. At E the transformation is completed, the steel is austenitic, and the work is ready for quenching to harden it, or to prevent a structural change back to pearlite. The furnace lid is removed and the work is quenched in oil, water, or air.

Fig. 119 shows a battery of hump furnaces with the attendant watching the time-temperature curves to locate the hump at which

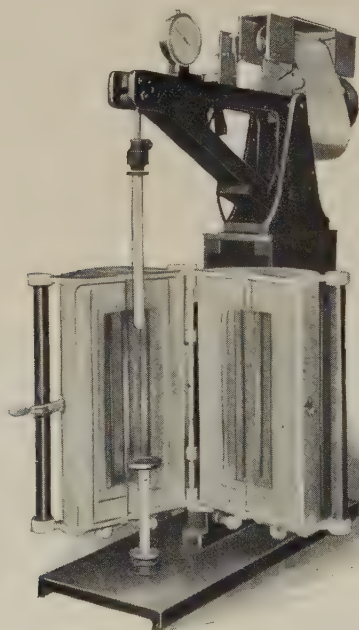


Fig. 121—Dilatometric Heat Treating Furnace.  
—Courtesy of Stanley P. Rockwell Co.

he will quench each furnace load. The method derives its name from the “hump” in the temperature curve.

### *Dilatometric Method of Heat Treatment*

A “dilatometer” set-up for heat treating is shown in Fig. 120. The tool or part is located at B inside the furnace A. L is a pyrometer for showing the temperature of the furnace at a point close to the work. C is a rod of quartz or metal having a low coefficient of expansion. D F is a lever actuated by rod C and

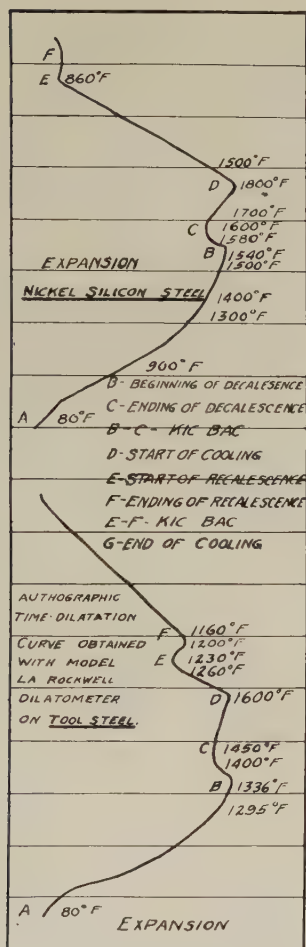


Fig. 122—Heating and Cooling Curves with a Dilatometric Heat Treating Furnace. — Courtesy of Stanley P. Rockwell Co.

moving about point D. E is a dial gage indicating the expansion or contraction of the work B, as rod C moves up or down. Cords F actuate pulleys HH and, in turn, a pen on drum G. As drum G is rotated by clock J, the pen traces a curve on the drum. The lever and pulley system greatly magnifies the expansion and contraction of the work, so the curve on the drum shows any possible

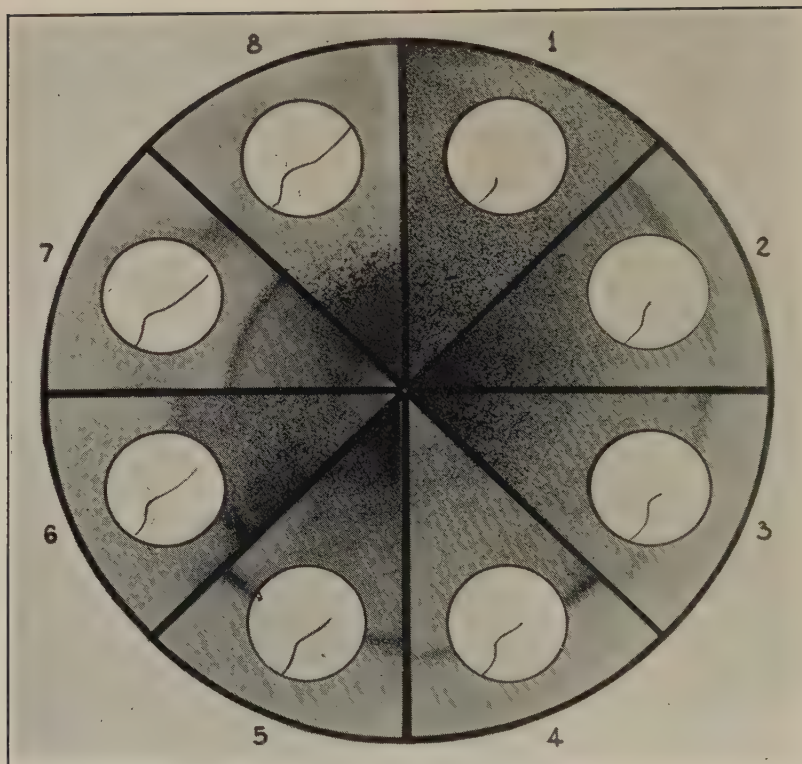


Fig. 123--Showing Steel Sections Hardened at Various Temperatures Around the Thermal Critical Points.—*Courtesy of Leeds and Northrup Co.*

variation in the length of work B. Fig. 121 shows a dilatometric furnace ready for operation.

The curves in Fig. 122 are typical heating and cooling curves taken with a dilatometer to illustrate the  $A_s$  transformation on both heating and cooling of two commonly used steels. Vertical lines denote temperature and horizontals denote expansion. The cold work is put in the furnace at temperature A and heated. At B the work contracts decidedly. This is the decalescence point at the start of the  $A_s$  (pearlite to austenite) transformation. At C the transformation or decalescence is ended. Heating is continued to D, where the heat was shut off and the work allowed to cool in the furnace. The work commences to contract at D, as would be expected with a lowering of the temperature. At E there is a

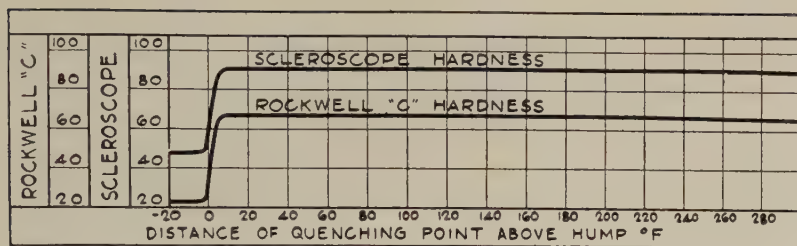


Fig. 124—Hardness Curves of Samples Shown in Fig. 123.—Courtesy of Leeds and Northrup Co.

noticeable expansion denoting the  $A_s$  (austenite to martensite, troostite, sorbite or pearlite) transformation or recalescence point. At F the transformation is complete and contraction continues on at a uniform rate in proportion to the drop in temperature.

In production hardening or heat treating the cover of the furnace is removed when the point C is reached, showing that the  $A_s$  transformation is complete, the work austenitic and ready for quenching. The steel is quenched in water, oil or air, depending on its nature, use, etc.

Both methods can produce excellent results. A uniform heating or expansion curve (except for the transformation) indicates too rapid heat input and nonuniform heating of the steel. Operators can easily be trained to pride themselves on the uniformity of their heating curves, and therefore on the uniform heating of steel being treated. The decalescence points and the point at which the transformation is complete are clearly shown. There can be no argument about the point or temperature at which the steel should be quenched.

The results of hardened steel produced by one of these methods is clearly shown in Fig. 123. Each of the eight segments shows the structure of a piece of steel heated and quenched from the temperature shown by the time-temperature heating curve in the small circles.

Number 1 was quenched just as decalescence started. The entire section is large grained showing no hardening.

Number 2 was taken after decalescence had advanced further. The outer portion of the round sample was nicely hardened. The center is still soft.

Number 3 shows further completion of decalescence and deeper hardening.

Number 4, taken when decalescence was just complete, shows maximum hardness penetration. In other words, the whole piece was as near as possible to the exact temperature desired for hardening or quenching from just above the completion of the  $A_3$  transformation.

Numbers 5 through 8 show the effect of quenching from temperatures above the  $A_3$  point. The outer portions are well hardened, but the centers clearly show grain growth which took place as the temperature was increased above temperature  $A_3$ .

Fig. 124 shows the hardness of these samples according to the Rockwell hardness tester scale "C," and the scleroscope. The low

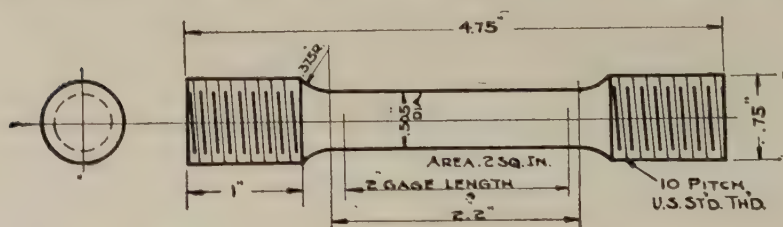


Fig. 125.—Diagram of 2-Inch Gage Length U. S. Standard Tensile Test Bar.

hardness at the start of each curve is the hardness, or lack of hardness of sample 1 which did not harden since it was quenched just below the  $A_3$  temperature. The hardness of samples 2 to 8 is uniform because the hardness determinations were made at the outside, well hardened portions of the samples.

## PHYSICAL TESTING

### *Tensile Test*

The word "tension" implies stretching and this is what happens to a bar of steel in the tensile test. Fig. 125 shows the usual test bar used in this country. A typical sample of the steel under test is machined to these dimensions and prick punch marks are made at points marked "2 inch gage length." The bar is clamped in the jaws of the testing machine shown in Fig. 126, and the load is slowly applied, causing the bar to stretch. A weight is adjusted along the long scale beam (shown at the right side of the picture)

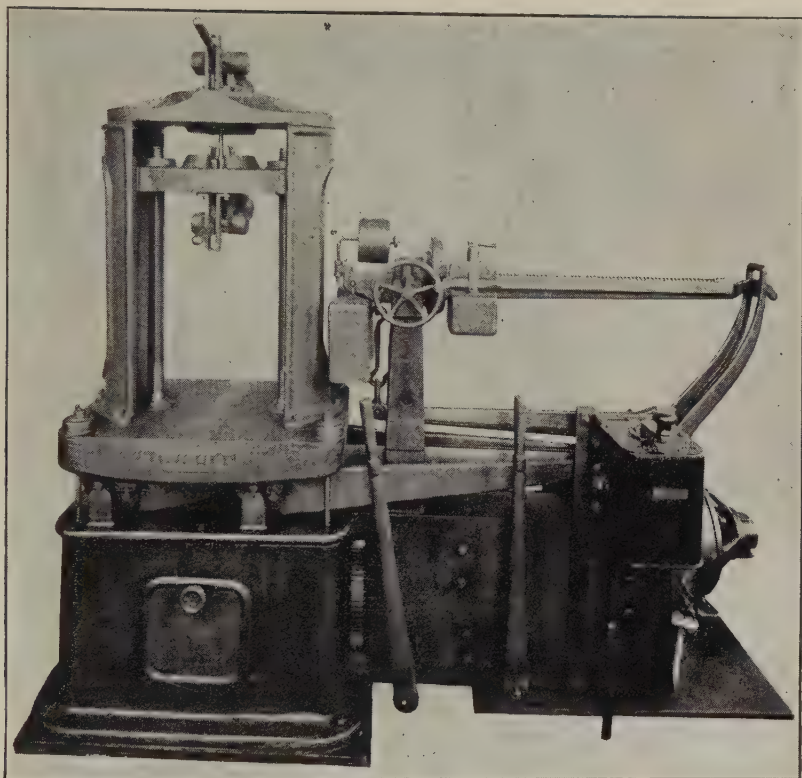


Fig. 126—A Tensile Testing Machine Capable of Exerting a Load of 60,000 Pounds.

to show the load being applied to the test bar. As the load is applied, the gage points (prick punch marks) move apart. When considerable load has been applied, a point is reached at which the bar stretches some distance without further load being applied, and the gage points move apart quite rapidly.

This is known as the “yield point,” often termed the “elastic limit.” Place a 1-inch bar on supports 24 inches apart, and strike the bar a light blow in the center. The bar will deflect, then return to its former horizontal position. Strike it a harder blow, then still a harder one. At a certain weight of blow, the bar will no longer return to its former position, but will remain slightly bent or will “take a permanent set.” This marks the yield point of the bar. Steel columns, beams, etc., all show this phenomenon.

The "yield point" marks the load at which the steel will no longer return to its original position. In practice, steel should never be stressed beyond its yield point.

As load is increased, automatic stretching ceases and the bar again continues to stretch in proportion to the applied load, up to the point at which the bar breaks. Just before rupture, the bar necks down slightly as shown by the bars in Fig. 127. This figure

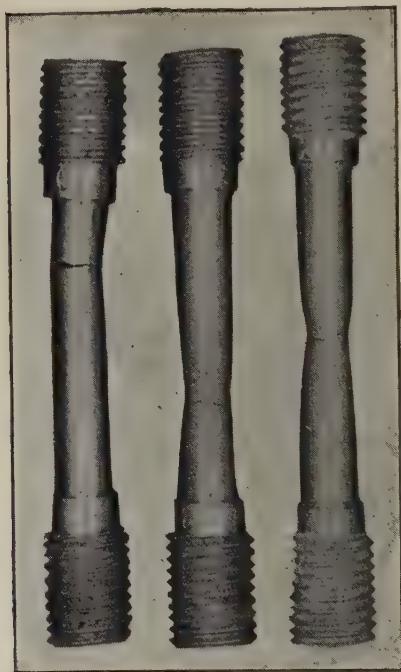


Fig. 127—Showing Standard Tensile Test Bars Pulled Apart in a Tensile Testing Machine.

shows three ruptured test bars that have been slipped together after rupture. The *tensile strength* marks the maximum load that steel can possibly support. It is the load applied through the machine just as the bar breaks.

The ratio of increase in gage length after rupture to the original gage length (2 inches) is termed *elongation*. The ratio of the difference between the original cross sectional area of the bar and the cross sectional area at rupture to the original cross sectional area is termed *reduction of area*. The elongation and reduction of

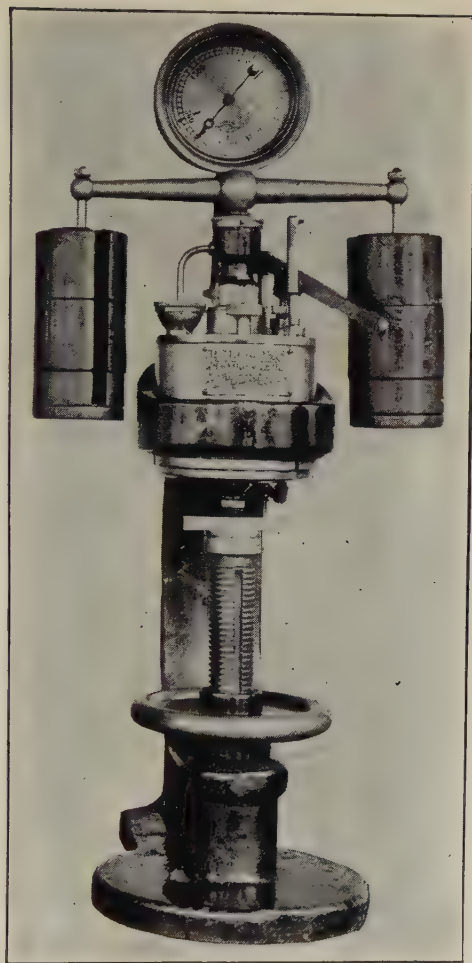


Fig. 128—Brinell Hardness Testing Machine.

area are measures of the ductility of the steel. Yield point (measured in pounds per square inch) is a measure of the maximum load steel can withstand without taking a permanent set. Tensile strength (measured in pounds per square inch) is a measure of the maximum load steel can possibly withstand.

#### METHODS OF DETERMINING HARDNESS

The following are the most usual commercial methods of hard-

ness testing now in use and they are given in the order of their historic development:

1. The file,
2. The Brinell hardness testing machine,
3. The scleroscope hardness tester,
4. The Rockwell hardness testing machine.

### *The File Test*

The file is the most generally used method for quick or preliminary investigation of surface hardness. If a good, sharp file is

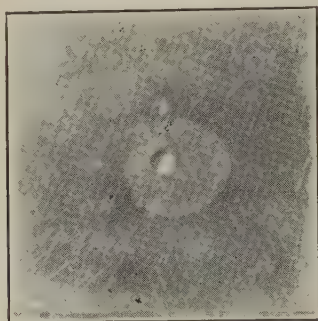


Fig. 129—Showing a Typical Impression Made in a Block of Steel With the Brinell Hardness Testing Machine.

placed against the hardened surface of a piece of metal with considerable pressure and given a forward movement, the file will clearly detect whether the surface is hard or not. The ability of the file to dig in or slip over the surface is a measure of the hardness. The requirements are a good, sharp, flat file used intelligently.

Files are made from tool steel containing about 1.30 per cent carbon. The teeth may be regarded as a series of small chisels formed on the surface of the steel. If enlarged, each chisel might be likened to the tooth of a rip saw. The teeth are supported at the back so that a file cuts in only one direction. Files are made glass hard, and as such are often no harder than the hardened steel under test, so that when the file is pushed forward it slips or cuts accordingly as the steel is hard or soft. If pressure is applied on a backward motion the tendency will be to break off the sharp points

of the file teeth because they have no support in that direction.

Let us assume that an inspector is testing a small blanking die with a sharp corner. The usual procedure is to push the file over the sharp corner at an angle of about 60 degrees, and perhaps to pull it backward under the same pressure. Under no condition should pressure be applied on the return stroke of the file.

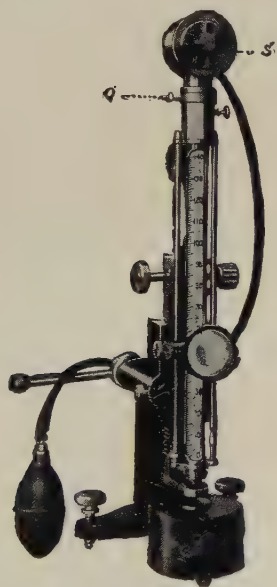


Fig. 130 — Shore Scleroscope in Which the Operator Notes the Rebound of the Hammer in the Instrument.

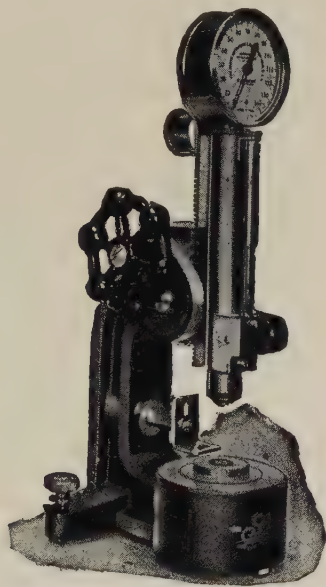


Fig. 131 — Shore Scleroscope in Which the Rebound of the Hammer is Recorded on the Dial.

To illustrate this point, in a large plant a man was testing a lot of carburized work with a file. The work was cylindrical in section with projecting sharp corners. Picture this man rubbing the file backward and forward over these sharp corners and over the cylindrical section. The writer said to him: "How long does one of those new files last?" "Oh!" he said, "I don't know, I use a couple a dozen a day." He was uselessly wearing out the files and was not securing the proper production per file.

When using the scleroscope, Brinell or Rockwell hardness testers, the surface to be tested should be freed from scale by grinding with a commercial grinder using a fairly fine grinding wheel.

The specimen should be chucked firmly in place. Details of all three methods are given in the HANDBOOK of the American Society for Steel Treating.

### *The Brinell Method*

This method of testing measures the ability of the metal to resist the penetration of a small, hardened steel ball when pressed into the metal by a gradually applied force. For the harder metals a 10-millimeter ball is employed and a pressure of 3000 kilograms is gradually applied for 30 seconds. For softer metals, the same ball is used and a load of 500 kilograms is applied for 60 seconds. The area of the impression and diameter of the hole is used to compute the hardness according to an arbitrary formula. Fig. 128 shows a Brinell hardness testing machine and Fig. 129 shows a Brinell hardness impression in a small block of steel. This method is not very accurate for testing exceptionally hard steel because of the danger of crushing or flattening the ball, thereby giving a false reading. The Brinell impression covers more of the sample than any of the three machine testing methods enumerated.

### *The Scleroscope*

In the Shore scleroscope, Figs. 130 and 131, a small diamond faced tup is dropped from a fixed height against the surface being tested. In the instrument shown at A, the operator reads the height tested. In the instrument shown in Fig. 130, the operator reads the height of rebound of the tup. In the instrument shown in Fig. 131, the height of rebound of the tup is recorded by the dial. The height of this rebound of the tup is taken as the measure of hardness, according to a fixed scale. The tube must be plumb to eliminate friction of the descending tup and the surface must be exactly at right angles to the fall of the tup. The scleroscope is readily portable, can be used on large pieces that cannot be moved easily, and does not seriously injure the surface being tested.

### *Rockwell Hardness Testing Machine*

The work being tested is elevated to position by means of an adjustable chuck or anvil. A minor load of 10 kilograms is first applied to hold the specimen in place, then the major load is ap-

plied for five seconds by forcing a  $\frac{1}{16}$ -inch hardened steel ball into the work under a load of 100 kilograms (Rockwell scale B) or forcing a cone-shaped diamond into the specimen under a load of 150 kilograms (Rockwell scale C). The depth of the impression is taken as a measure of the hardness and is expressed according to an arbitrary scale; scale B using the steel ball, for the softer metals; and scale C using the diamond cone, for the harder metals.

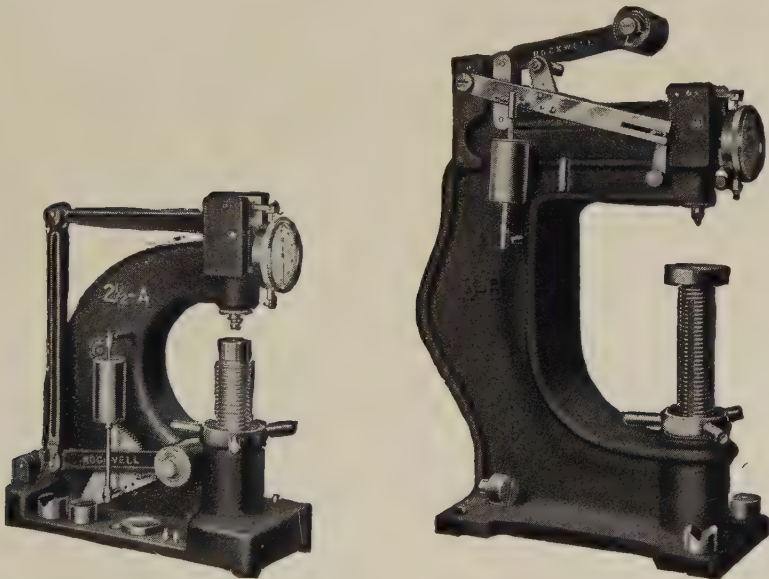


Fig. 132—Showing Two Sizes of Rockwell Hardness Testing Machines.

The Rockwell machine may be used on most all work, even on fairly thin sheet stock. For very large grained metals several impressions will have to be averaged as the penetration is so small that it may possibly penetrate but one grain at a single reading. Its operation is quite rapid.

#### *Other Physical Tests*

The tensile and hardness tests do not by any means cover all the physical tests in common use, but they are probably the two tests in most general use. Compression, shear, alternate stress, notched toughness and torsional tests are all in common use. They are explained in detail in standard text books.

## LECTURE V

### HARDENING, QUENCHING, TEMPERING, AND CARBURIZING

#### *Heating for Hardening*

The process of hardening is applied to steel containing sufficient carbon and alloys to harden by the formation of martensite when the part is quenched. The hardening process comprises two operations (1) heating to above the  $A_{c_3}$  temperature and soaking to form austenite and (2) quenching at the proper rate to form martensite, the first decomposition product of the austenite, or to form one or more of the other decomposition structures, troostite, sorbite, or pearlite.

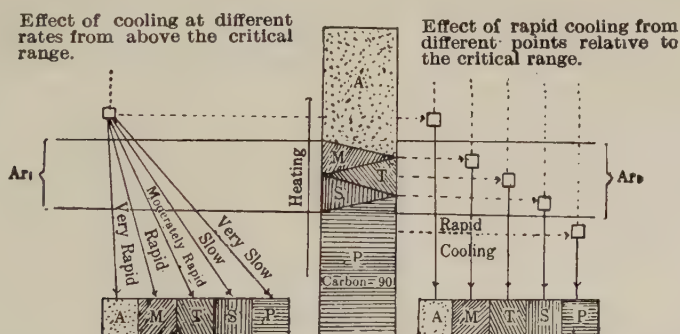
Austenite forms in plain carbon steels above the  $A_{c_3}$  temperature, as shown in Fig. 79. Heating for hardening, like heating in other thermal operations, should be slow and uniform so that the entire mass of metal will be brought to heat, as nearly as possible, at the same time. Too rapid heating sets up internal strains that may easily cause small internal ruptures, or even large cracks. Parts should be held at the high temperature for sufficient time to bring all portions of the part up to temperature. For small tools, a quarter or half an hour may suffice. Larger parts such as forgings or castings may require several hours soaking at above the  $A_3$  temperature. A much used rule is to soak the mass of steel one hour for each inch of thickness at its thickest section. The eye is a valuable aid to proper soaking at temperature. All portions of the steel mass should be at the same color before the steel is quenched or cooled.

The necessity for slow and uniform heating cannot be over-emphasized, especially with intricately shaped pieces of varying section where one part is thick and an adjoining part is thin. Too rapid heating will cause the thin section to crack away from the heavy section. It may even be necessary to shut off the fire or heating element for a short time to allow the mass of steel to equalize with the temperature of the furnace. But long and slow heating cause scale. Be sure that the furnace atmosphere is either neutral or reducing. Coke or charcoal charged into the furnace with the load of steel will help absorb any free oxygen that may

enter through the ports or cracks of the furnace, or with the oil or gas mixture if the furnace is fired with oil or gas. Intricately shaped parts may be packed in pipes or tubes filled with sand to prevent the oxidation, scaling or burning of delicate edges.

### *Hardening*

We shall now proceed to quenching of properly heated steel. Let us recall the statement that the natural tendency of the carbon is to separate and get away from the iron, provided an opportunity is offered. That opportunity is sufficient time in cooling through the critical range as may be noted in Fig. 133. This figure illustrates schematically the proper speed of quenching to



Legend: P=Pearlite, A=Austenite, M=Martensite, T=Troostite, S=Sorbite.

Fig. 133—Diagram Showing the Rates of Cooling Necessary to Form the Principal Microconstituents in a Eutectoid Steel.—*Courtesy of Sauveur.*

retain any of the five principal microconstituents in a eutectoid steel. If heat could be removed instantly or very rapidly, austenite might be retained as indicated. The retention of this constituent is possible in a number of different alloy steels because some alloys aid in speeding up the quench.

It is a practical impossibility to retain austenite at room temperature in carbon steel under regular heat treating procedure. Even with drastic quenching from the  $A_{c3}$  point, austenite breaks down into martensite in hardened tool steel. If cooled with moderate speed as in oil, there is a possibility of retaining some troostite (tempered steel). On slow cooling in very thick oil or in air,

sorbite will probably predominate. On very slow cooling, such as in a furnace, the steel will revert back to pearlite. It is doubtful if any single structural constituent can be retained uniformly throughout the mass. The reader will recall the statement in lecture III, that the transition structures can be formed with greater regularity by rapidly quenching the steel to retain martensite, than by decomposing the martensite by means of an appropriate tempering operation.

### *Quenching Media*

The real function of a quenching medium is to conduct heat away from the mass at the desired speed. In the removal of heat from steel, uniformity in the rate of cooling is quite as desirable as uniformity in the rate of heating the different parts, but the uniform removal of heat is often impossible on account of the rapid rate of cooling necessary to harden steel to a given depth. Since the rate of cooling controls the hardening process, the selection of a proper quenching medium is of great importance. The size, shape and contour of steel to be quenched must also be studied.

Reliable quenching media and methods are as follows:

1. Ice-brine,
2. Brine at room temperature,
3. Lake, city, or river water,
4. Oils,—depending upon their viscosity,
5. Time quenching in either oil or water,
6. Air cooling,
7. Furnace cooling,
8. Spray quenching.

The speed of heat withdrawal depends upon the quantity and properties of the liquid. The properties of a cooling medium are its specific heat, its thermal conductivity, viscosity, its latent heat, boiling point, burning or flash point (if an oil) and its initial temperature. The property of conductivity effects a more or less rapid change of heat between different parts of the bath. Specific heat is a measure of the quantity of heat that can be absorbed by a volume of fluid in raising its temperature. Viscosity is an index of the ability of the medium to flow or to be set in motion, e. g., lard oil is quite viscous but kerosene has a low viscosity. Viscosity also determines to some extent the rate of formation of

the vapor or steam around the steel. In a viscous liquid, vapor bubbles cannot easily be brushed from the surface of the steel. Bubbles on the surface of the steel tend to retard the cooling, and to form soft spots.

Since the speed at which heat is transferred from one body to another varies directly as the difference in their temperatures, it is evident that the initial temperature of the quenching liquid must affect the rate of cooling. Water is one of the most efficient media for rapid cooling and is widely used commercially. Its specific and latent heats, and its viscosity are very low, these properties favoring its cooling power. It is cheap and is available in quantity. It can be circulated and directed under pressure to any part of the bath or against the metal in order to convey steam away from the block of steel. A solution of salt and water (brine), gives excellent results on medium sections of steel because salt water does not form steam readily. This is one of the reasons salt water cannot be used in a steam boiler. Water sprayed under pressure is a very rapid cooling agent because it forces the accumulated vapor or steam away from the steel and allows the cooling spray to make direct contact with the hot steel. Further, it can be directed under pressure to any part of the steel requiring especially rapid cooling.

Oil cools slower than any of the foregoing because a deposit of charred oil is formed on the surface of the heated steel. This keeps the oil from making direct contact with the hot metal. Oil quenching media include: Mineral oil, kerosene, fish oil, whale oil, cotton seed oil, linseed oil, lard oil, and special animal hydrocarbon oils. Mineral oils have proven to be highly satisfactory in plants where the quenching bath temperature is kept low by artificial cooling. If the oil is not artificially cooled, it breaks down and thickens with heat, forming a residue which slightly varies the quenching rate. Kerosene is dangerous unless kept at a temperature below its burning point. Fish and whale oil have the offensive odor of decaying fish and are open to the same objections as seed oil. Cotton seed and linseed oil become gummy from oxidation, resulting in increased viscosity which seriously affects the quenching speed. Lard oil has a tendency to become rancid. Many of these objections have been overcome by the preparation of the specially blended quenching oils. Artificial cooling of oil

is necessary when continuously handling large quantities of metal. There are numerous other quenching media such as lead, carbonate of lime, mercury, milk, soda, tallow and wax. These are sometimes used for quenching small and delicate parts.

As stated, the degree of hardness is directly proportional to the quenching speed. This varies directly with viscosity of liquid and its specific heat. Viscosity is a measure of the fluidity, draining qualities and ability of the medium to dissipate absorbed heat by the natural circulation or convection of the liquid. An oil of low fluidity has relatively high viscosity and drains slowly from the steel, wasting considerable oil. The transfer of the heat through a body of oil is sluggish. Specific heat is a measure of the relative capacity of liquid to absorb heat. The specific heat of water is 1.000 and the specific heat of a special animal hydro-carbon quenching oil is about 0.490. A given weight of this oil has about 49 per cent the capacity for heat possessed by the same weight of water having the same temperature. Otherwise expressed, the quenching speed of hydrocarbon oils is approximately one-half that of water.

The specific heat of ordinary quenching oil is about 0.500, therefore twice as much oil would be required to handle the cooling if the same range in temperature between the temperature of the hot steel and the quenching solution is to be maintained. The volume of water is seldom a limiting factor, but in oil quenching, the volume of oil is often low. A good practice is to provide one gallon of oil to a pound of steel quenched per hour.

Certain characteristics of the various quenching media are worthy of notice. Cooling power of water does not vary appreciably if the water is kept below 125 degrees Fahr. At 125 degrees Fahr. the power for surface hardening has not diminished, but the ability to quench deeply is gone. For water above this temperature (hot water quenching), the results are doubtful, cooling in the early stages is low, and hardening power is slight. As the temperature of the steel drops, the relative cooling rate increases. The cooling rate at the lower temperatures of the mass of steel, say 300 to 700 degrees Fahr., where strain means cracking, is often so rapid as to cause rupture. It results in irregular hardness and excessive cracking. Great care is necessary when water quenching intricate parts.

Brine cools rapidly while the piece is at high heat, and more slowly as the temperature of the work is lowered. This is a very desirable feature when hardening thin sections of high carbon material which require a fairly high tempering temperature. The hardening of cutting edge tools, like an axe, is a good example. Brine is not well suited for quenching parts that require extreme hardness, since it results in slower cooling at the temperature at which the work later is to be tempered. Brine may cool so slowly that soft work results. Carburized parts should not be quenched in brine. Caustic soda solutions cool steel rapidly at the higher temperatures, and more rapidly in the lower temperature range. For drastic quenching, as with carburized work, this solution is very dependable. The concentration may vary considerably but as generally used, it contains about 10 per cent caustic soda. The dependability of this solution has led to its wide use where quenching must be done under the stress of heavy production. Very large loads of steel can be handled without questioning the temperature of the solution.

There are many other quenching solutions that might be touched upon but the ones suggested are in quite common use. In using any of these quenching media, particularly in mass production, one can easily acquire direct information as to the value of any quenching media by the following simple experiment. Select a definite size block of material under test, drill a hole large enough to insert a thermocouple in the center, and seal it so it will remain in contact with the iron or steel under test. Heat the block to a definite temperature and quench it in a definite quantity of the quenching solution under test. Note how rapidly or how slowly the block is cooled to a definite temperature. Record the results for future reference in similar tests. Many tests of this character have been carried out by steel companies, the Bureau of Standards and the manufacturers of quenching oils. These data are available in the literature and upon request from the firms.

Partial quenching in water followed by completing the quench in oil is sometimes employed. The process is to immerse in water for a given length of time to acquire surface hardness, then to remove to the oil bath to allow the center to cool more slowly and without losing surface hardness. This method will often provide greater hardness than an oil bath, and avoid the danger of crack-

CRITICAL COOLING RATE

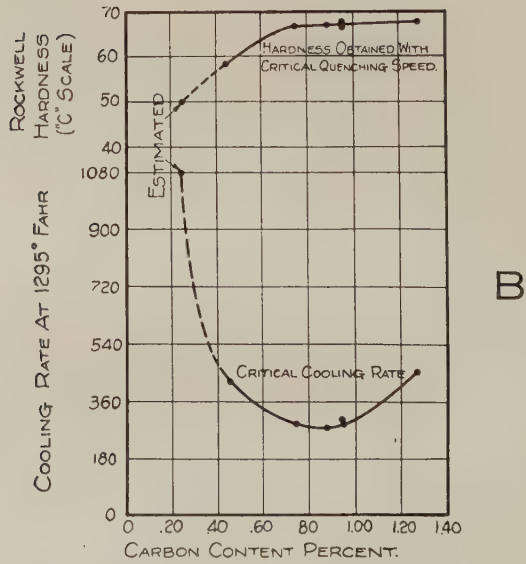
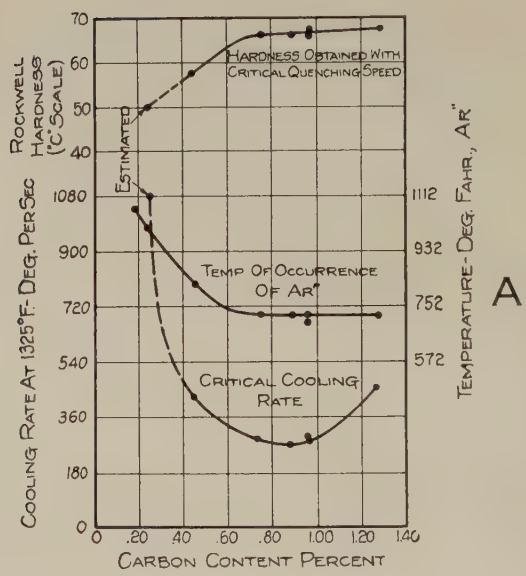


Fig. 134—Effect of Carbon Content on the Critical Cooling Rate for Carbon Steels. A—When Quenched from an Initial Temperature of 1325 Degrees Fahr. B—When Quenched from an Initial Temperature of 1295 Degrees Fahr.—Courtesy of French and Klopsch.

ing in water quenching. On the whole, increased hardness in oil quenching may be obtained by increasing the flow of oil, thus accelerating the quenching velocity.

### *Critical Cooling Rate*

For each block of steel there is a critical cooling rate. If the material has been held at a temperature above the  $A_1$  range for some time, the steel must be cooled at a definite minimum rate to accomplish hardening. This minimum or critical cooling rate is usually determined with reference to speed at which the steel passes through its upper critical range during cooling. A much-used reference temperature is 1325 degrees Fahr. Fig. 134A shows the critical cooling rates and the resulting hardness for steels of varying carbon content and small section. For half-inch round bars, a quenching speed of about 270 degrees Fahr. per second will properly harden a steel containing 0.90 per cent carbon; a rate of 285 degrees Fahr. per second will harden a 0.75 per cent carbon steel; and 400 degrees Fahr. per second will harden a 0.50 per cent carbon steel. The 50-point carbon steel shows considerably less hardness than the 65-point carbon steel, as would be expected. For steels containing 65 to 120 points of carbon, the hardness imparted by the critical cooling speeds is substantially the same. Fig. 134B shows the critical cooling speeds for carbon steels quenched from 1295 degrees Fahr. The critical cooling rates and the resulting hardness are substantially the same as when quenched from a temperature of 1325 degrees Fahr. This shows (1) that it is permissible and necessary to heat steel to a temperature somewhat above the critical temperature in hardening and (2) that there is a minimum cooling rate, at which steel can be hardened. The critical cooling rate increases and is not so sharply defined as the cross section of the steel object is increased. (3) A quenching medium must provide sufficient cooling power to equal or exceed the minimum cooling demand of the steel as measured by its critical cooling rate.

As stated, the rate or velocity at which the quenching medium can conduct heat away from the metal must be equal to or greater than the critical cooling rate if the metal is to harden properly. Fig. 135 shows the cooling velocity of water and two types of oil. The velocity of cooling was measured at 1325 degrees Fahr., just

above the  $A_{3-2-1}$  critical temperature at the center of the half-inch round samples of steel. The samples were heated to the quenching temperatures indicated and the velocity of quench was measured at 1325 degrees Fahr.

The Bureau of Standards, and some of the steel companies have carefully studied the quenching power of various media, the

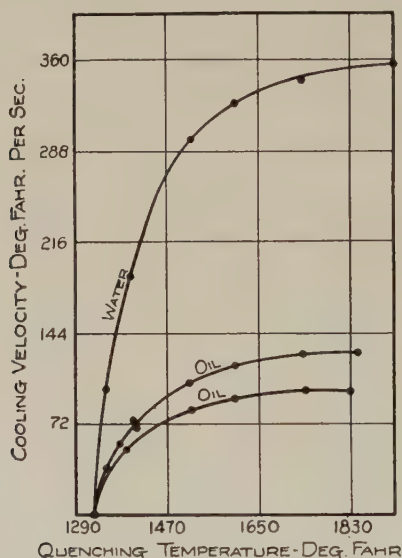


Fig. 135—Effect of Quenching Temperature on Center Cooling Velocity at 1325 Degrees Fahr.—*Courtesy of French and Klopsch.*

effect of cooling from various temperatures, the effect of the mass of steel being quenched, etc. They have determined the various engineering constants, so that it is possible to prescribe definite quenching treatments without a great amount of cutting and trying. This material is available in the general literature, and from any of the steel companies.

It will be noted that the quenching velocity of water becomes greater as the rising quenching temperature is increased up to 1550 degrees Fahr., but the quenching does not speed up greatly with any increase in temperature above this point. It may also be noted that oils do not show increased quenching velocity above 1550

degrees Fahr. Oils do not show the variations of quenching velocity that appear in the water.

In the discussion of the iron-carbon diagram in Lecture III, we saw that in slow cooling from the  $A_3$  temperature range to well below the  $A_1$  temperature range, the steel changes from austenite to martensite, then to troostite, then to sorbite, and finally pearlite. It was shown that rapid cooling from the  $A_3$  and especially rapid cooling through the critical ranges to below the  $A_1$  checked the break-down from austenite into pearlite, retaining one

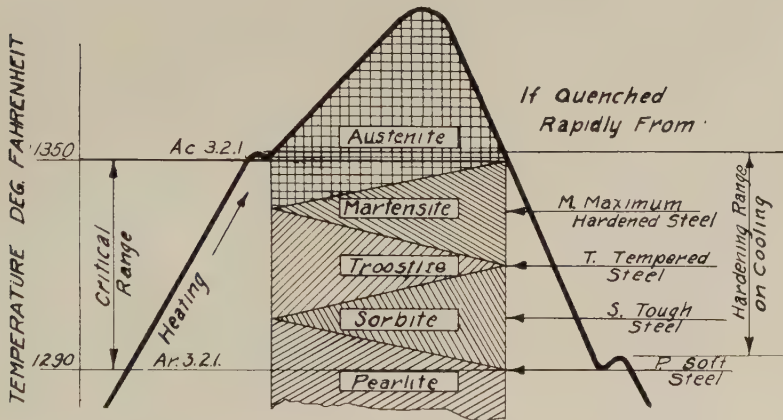


Fig. 136—Transition Structures in Hypereutectoid Steel Illustrated Schematically.

or more of the intermediate structures, depending on the rate of cooling. When steel is drastically quenched, the martensite thus formed can be broken down into the intermediate structures by tempering (drawing) at a fairly definite temperature.

Fig. 136 shows the  $Ac_{3-2-1}$  and the  $Ar_{3-2-1}$  for hypereutectoid plain carbon steels. The transition structures are shown schematically, and in the order in which they form. The rate of cooling from the  $Ac_{3-2-1}$  to well below the  $Ar_{3-2-1}$  determines the structure or structures that will be present when the steel is cold. Fig. 137 shows the effect of alloys such as 12 per cent of manganese, or large percentages of nickel in suppressing the critical points completely. The austenite shown in Fig. 81 is an example of this suppression. It contains 12 per cent of manganese and was quenched in water from about 1850 degrees Fahr. Fig. 138 represents the effect of certain alloys which widen the range between the  $Ac_{3-2-1}$  and the

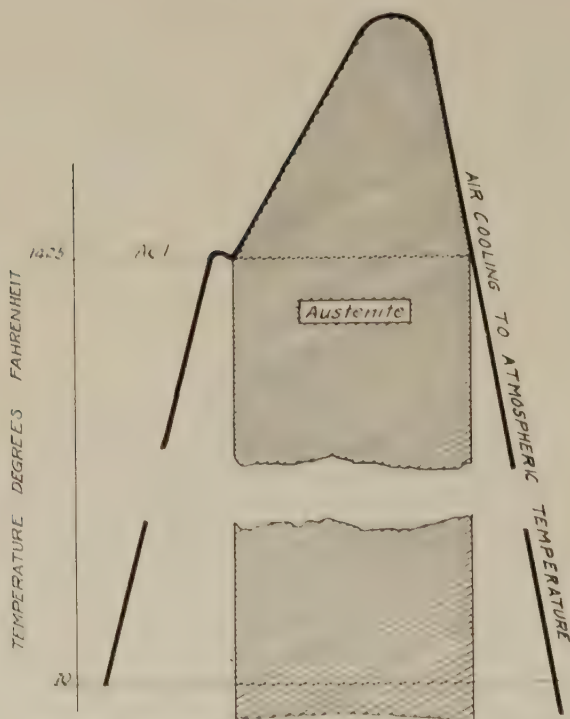


Fig. 137—Suppression of the Critical Ranges by Certain Alloys, Illustrated Schematically.

$Ar_{3-2-1}$ , resulting in a steel that is more responsive to the less drastic cooling media, such as oil. Small percentages of vanadium, chromium and molybdenum have this property. These steels are very useful in parts that require great toughness or hardness. If made of plain carbon steel and quenched in water, the action would be so drastic that there would be great danger of cracking the part or causing internal rupture. By using such alloys, the less drastic media will give the desired sorbite, troostite or martensite structures without the risk of cracking or internal rupture.

The comparative depth of hardness, retention of fine-grained structure and the effect of excessive heating above the critical temperature between carbon steel quenched in water and alloy steel quenched in oil is well illustrated by the fractures shown in Fig. 139. C represents carbon steel and A, alloy steel. The characteristic structure of these two steels when quenched from just above the critical range is represented at 3C and 3A.

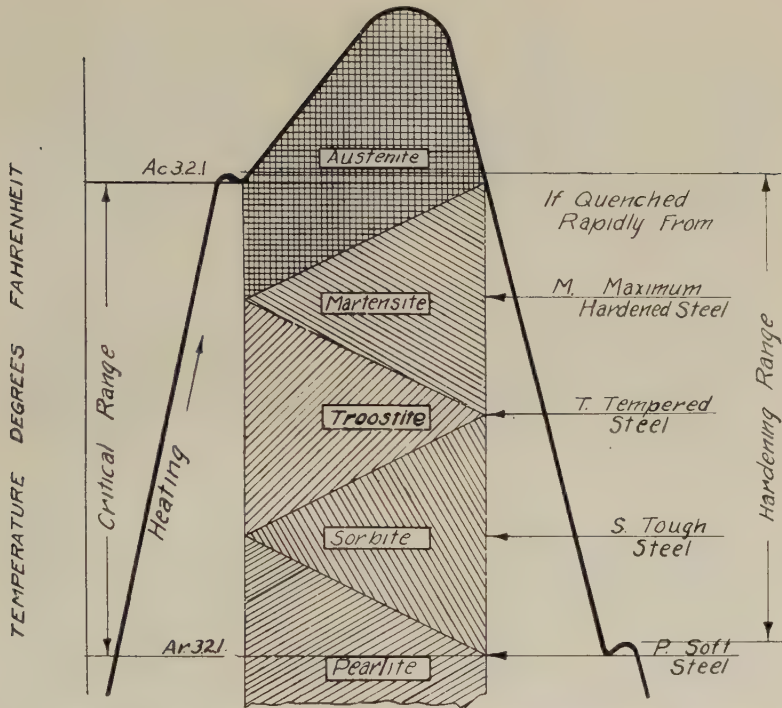


Fig. 138—Transition Structure in Certain Alloy Steels Which Widen the  $Ac_{3-2-1}$  to  $Ar_{3-2-1}$  Thermal Range, Illustrated Schematically.

## TIME QUENCHING

This phase of the subject was mentioned briefly under various headings. It is not always taken full advantage of in industry, probably because it is a bit complex and time-consuming. The writer has carried out many practical experiments and has proven its value in service. In demonstrating its application on a lot of tool steel an eminent metallurgist was an interested spectator. At the conclusion of the demonstration he made the following remark: "While your time quenching is not theoretically correct, Keller, you are certainly getting away with it and to be frank, the metallurgical world, as a rule, has not taken cognizance of the method." Upon proving its advantages, the officials of a well-known firm installed a heat treating equipment and pyrometer for determining temperature. They are now successfully treating all

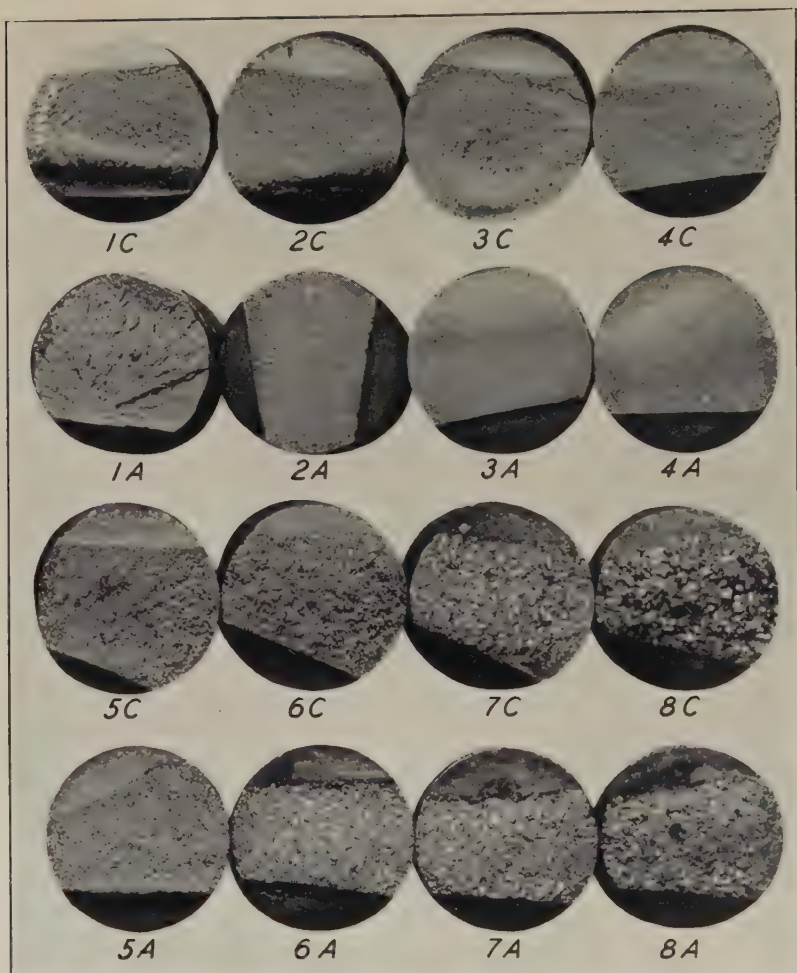


Fig. 139—Fractures of Plain Carbon Steel C and Alloy Steel A Showing the Comparative Depth of Hardness When Quenched at Various Temperatures Below and Above the Critical Temperatures.

parts of machinery, power equipment and tools by heating the material above the  $A_{c3}$  point, then time-quenching in water or allowing it to air cool to form the desired structures. In most cases, time quenching does away with the tempering operation.

The following instance will give the reader some idea of the value of the many types of time-quenched material. In a quarry the stone is cut into blocks by a channeling machine. A self-con-

tained power unit travels on a track. The mechanism for cutting the stone consists of a moveable steam cylinder with a cross-head between guides into which are clamped five channeling drills. These drills vary in length from 36 inches to 15 feet. The cutting edges are made something like a chisel, except that they are spread out for clearance. Three of these drills cut at right angles to the line of travel and the two center drills are made to cut diagonally. The pounding of these drills through the rock may be likened to the pounding of a steam hammer, with blows ranging from 180 to 360 per minute.

Upon investigation it was found that the tool steel in use was the usual mill stock, formed in sharp instead of rounded corners. The only heat treatment given this material was hardening and tempering of the cutting points in an ordinary forge. It was assumed that the constant pounding of these drills created so-called crystallization. The failures were, of course, due to fatigue, minute cracks starting from the sharp corners of the drill. Failures of these drills were frequent and expensive. Many blacksmiths were employed to weld this tool steel together with the hope of making it stronger, but, of course, more failures occurred. In one instance we found one bar 12 feet long with 14 welds in it. By enumerating all cost items such as lost time of the machine, changing, etc., the cost per weld was \$2.07.

With the heat treating equipment, the firm uses the same type of steel as previously used, except that it is rolled with a  $\frac{1}{16}$ -inch radius on the corner. The cross section of the material is  $1\frac{1}{8} \times 1\frac{3}{8}$  inches. When the points of the drills are sharpened and time-quenched, heat treatment is as follows: Heat to 1425 degrees Fahr., time quench in the water for nine seconds, and straighten while still warm. This treatment develops toughness and resiliency similar to automobile springs. Such treatment is now a fixed practice with this concern.

The following experiment will quickly show its value to anyone interested. Select from the same bar two pieces of  $\frac{5}{8}$ -inch round stock about 8 inches long. Clamp one end in the vise with about 4 inches projecting. Strike lightly with a hammer and attempt to bend. Continue bending until it fails, noting the force required to bend and rupture. Heat the other piece to above the  $Ac_3$  point and quench for three or four seconds. When cold, bend

in the vise in the same manner and note the results. Increase or decrease the time quenching period in order to produce the desired characteristics in the material. There are many applications in the metal trade industry for this method of quenching, provided that it is carried out intelligently.

### QUENCHING IN STILL LIQUIDS

All sections of metal should be quenched in the direction of the longest axis with the movement in the liquid parallel to the axis. Side or circular motion may be likened to a boat going up stream leaving a void or vacuum behind it. Naturally, steel quenched in this manner will cool on one side and then on the other by reversal of such motion. The ideal would be to have a sufficiently large volume or circulation of the quenching medium. Circulating the liquid by compressed air is undesirable because the air bubbles will come in contact with the steel and cause soft spots. In fact that is the way carburized mottled steel is made. The air in contact with the steel oxidizes it, hence the variable colors.

### SPRAY QUENCHING

The shortening of lengths, distortion, warpage, and cracking of metal is due chiefly to localized cooling, i. e., some parts of the steel are cooled faster than other parts. This phase will be covered in detail in the sixth lecture. This brings us up to what the writer considers an ideal cooling method, that of "spray quenching", in which the liquid is directed under pressure to the parts that are to be cooled quickly. Take, for instance, the quenching of a stamping die. When such a die is immersed in still water or oil the corners cool first and the direct center is the last to cool. Cooling of the outer portion of the die would cause compressive action upon the hot, soft interior or on the impression in the center of the die. If the die contains a hole or space, after the die is hardened and tempered, the hole must be lapped to remove that portion of the metal that has been "pushed in," so to speak, while the outer portion of the die was cooling.

Such a die might be dropped into the oil and onto a jig or rest, equipped with a trigger placed so that upon contact, an oil spray diametrically opposite to the center of the die would auto-

matically release. The spray could be adjusted to cool the center portion or working part of the die quicker than the outside. This would probably prevent the corners from breaking off and distortion of the impression as above mentioned.

Again, picture one attempting to quench a plate of tool steel  $\frac{3}{8}$ -inch thick, 24 inches long and 18 inches wide in still water to prevent warpage. Naturally the outer ring or edges would cool first, putting the warm center in compression and causing it to hump in one direction or the other. This procedure would bring the center up to hardness required. Then picture that same piece being immersed in still water on a jig making contact with a trigger and instantly releasing two sprays of water diametrically opposite from the center, with the water under high pressure. The center would cool faster than the outside. This process would eliminate much warpage and cracking, and hardness in the center would be greater.

The application of this principle is well outlined and illustrated in a discussion of the high temperature quenching of cold heading ball dies, by Frank L. Wright, in the February 1928 issue of the TRANSACTIONS, of the American Society for Steel Treating; also one by L. S. Cope, in the July 1928 issue of the TRANSACTIONS.

#### TEMPERING (DRAWING)

In the process of hardening steel, internal and external stresses are set up in the material. These stresses sometimes cause rupture several hours after quenching, therefore tempering should *immediately* follow the quenching operation. Let us attempt to picture the cause of these stresses. When a steel is heated above the critical temperature essential for hardening purposes, the metal expands  $\frac{1}{8}$ -inch to the foot. If we attempt to quench a 12-inch cube it will be well to remember that while the block is in a heated state, it is  $\frac{1}{8}$ -inch longer in each direction than when cold. In quenching the surface, the outer layers cool first, shorten their length, and thereby put compressive stress on the center mass. When a sufficient amount of the surface material is cooled deeply enough, it compresses the inner material to some extent. When recalescence occurs in the interior mass, it expands. As the cold surface will not allow expansion, it sets up a surface stress on the material which is not injurious unless the mass has

a very thick, hard shell. It is the continued cooling of the outer material that sets up internal stresses. One of the principle objects in tempering is to relieve such stresses. Hardening imparts maximum strength accompanied by unusual brittleness; therefore, the surface is tempered to relieve this condition and to impart the required physical qualities to the metal. There are a few factors to be considered in the initial heating of hardened tools because of the danger of internal rupture by too sudden expansion of the

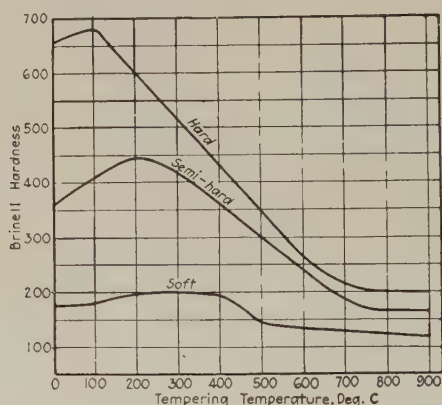


Fig. 140—Effect of Tempering on the Hardness of Hardened Steel.—Courtesy, Jeffries and Archer.

hardened surface. The tempering liquid or furnace atmosphere should not exceed 200 to 300 degrees Fahr. when the cold metal is immersed. This will afford an opportunity of gradually heating the surface, causing the release of internal strains. The tools or parts should be placed in a wire basket or each tool should be suspended by a wire to prevent contact with the side of the oil container. The temperature is increased slowly to the desired temperature and held for a given time as previously stated.

The carbon in a hardened steel is in a finely divided state. If the hardened steel is reheated for tempering purposes, it affords the carbon an opportunity to again re-assemble. If a piece of steel is drastically quenched to form martensite, then tempered, at rather definite temperatures the structural constituents, martensite, troostite, sorbite and possibly pearlite are formed in the order named.

Fig. 140 by Grard shows that hardness increases slightly at the lower tempering temperatures. It is quite possible in quenching for hardening that very fine quantities of austenite are trapped and have not changed into martensite. The lower temperatures in tempering probably cause these last traces of austenite to change into martensite. Since austenite is soft, and martensite is very hard, this change accounts for the increase in hardness at these lower tempering temperatures.

### *Time Versus Temperature in Tempering*

Uniformity of temperature throughout the hardened mass is just as important in tempering hardened tools as in all other thermal operations because it is the correct tempering that relieves quenching strains and puts the finished touch to the tool or part. The inefficiency and failure of tempered tools may often be traced to the fact that such tools and parts have not been given sufficient time in tempering to gain uniformity of temperature. It is supposed by many persons that if hardened steel is tempered at a fixed temperature for a reasonable length of time, any extension of time at that same temperature will decrease the hardness. Evidence is available to prove that the converse is true.

It has been stated by a reliable authority that if thirty minutes is the allotted time for soaking at a definite tempering temperature and the time is extended to two hours, the efficiency of the tool life will be increased. F. L. Wright in the "Tempering of Cold Heading Dies" makes this statement, "The time at the tempering temperature was varied and for the mass used in these tests it was found that no appreciable difference in their life (life of the dies) resulted when times of more than one hour at temperature were used, but shorter time resulted in early failures due to flaking."

### *Tempering in Boiling Water*

Grard's curve, Fig. 140, clearly shows no loss of hardness by immersing a hardened tool in boiling water. According to this curve the tool increases in hardness. In other words, at the boiling point of water the maximum hardness of the steel may be developed. The increase of hardness is perhaps due to the change of the last trace of austenite to martensite. It has also been dem-

onstrated that the heating of hardened steel blocks or tools to this temperature relieves considerable internal and surface stress, provided the block or tool is left in the boiling water for a sufficient length of time for complete thermal saturation at that temperature. This process is available in a small shop by placing a bucket of water on a forge fire and immersing the quenched tools in the boiling water. It may be necessary to further temper the tools. By first tempering in boiling water the steel has an initial temperature of 212 degrees Fahr. and may immediately be transferred to any tempering process.

### *Oil Tempering*

If an oil tempering furnace or pot is equipped with a thermometer, the hardened steel may be immersed in the hot oil in preference to the hot water, heated to the temperature desired and held there for sufficient length of time. There is a limit to the temperature at which steel may be tempered by oil on account of the danger of fire.

### *Salt Baths*

If higher tempering (drawing) temperatures than those possible with oil are desired, a bath of salt may be used. Various salts can be secured for almost any desired temperature. Care should be used not to immerse moist tools in salt baths because of the danger of burns caused by spattering of the hot salt.

### *Lead Bath*

Lead may be used for tempering temperatures above 640 degrees Fahr. and is used to considerable extent for tempering temperatures up to 1100 degrees Fahr. The melting point of lead is about 610 to 630 degrees Fahr., so lead is of no value below that temperature. The melting point may be lowered by allowing tin with the lead.

There are three undesirable factors in the use of lead in tempering. First, it has a high specific gravity which necessitates arranging the material in jigs or weighting it down, otherwise the material would float to the surface. Secondly, if the surface of the bath is exposed to the atmosphere, a heavy coating of lead oxide

forms on the surface. This may be prevented to some extent by covering the bath with spent carburizing material. Thirdly, the lead has a tendency to stick to the material immersed and at times it is difficult to remove.

Lead is used to considerable extent for the tempering of high speed tools up to about 1050 degrees Fahr. It is also used as a quenching medium for high speed steel. If used for this purpose, the temperature should not exceed 750 or 800 degrees Fahr. as the immersion of the high temperature tool will increase the temperature of the lead bath. If hardened tools are to be tempered, they should be reheated slowly and uniformly by some other means before immersing in the high temperature lead.

### TEMPERING COLORS

Nature has provided a useful indication of the degree to which tempering has affected the steel by the formation of a surface film of oxide of iron. A piece of hardened steel is polished with an abrasive, usually a broken piece of grinding stone or emery paper, then reheated slowly to about 365 degrees Fahr. when a thin film of oxide of iron appears on the polished surface. As the temperature is increased this film of oxide becomes thicker and darker. A straw color is fair evidence of a temperature of about 480 degrees. At 600 degrees Fahr. a dark blue appears. With further increase of temperature the blue disappears gradually into a shade of green and then gray. If the metal is heated to a higher temperature, the red heat color will probably appear through the iron oxide or scale. The formation of scale begins at a low temperature, particularly when in contact with free oxygen.

Each color is closely indicative of a known temperature. This condition depends upon the time element. Temper colors indicate the temperature of the steel so long as the temperature of the oven or tempering plate is greater than the temperature of the steel, but when the steel is being kept at a definite tempering temperature for any length of time the colors do not represent the actual temperature of the steel. Darkening of the color from a light straw to blue or the like, may occur when the steel is held at the same temperature for a considerable length of time. Colors are fairly accurate under standard conditions if reasonable time is taken in tempering the steel.

The following incident should convince one that colors do not in themselves represent the true conditions. While in charge of an industrial plant a few years ago the writer handed a very intricate tool to a new tool dresser of some reputation, saying: "Pat, they are in a hurry for this tool. Take your time to prevent cracking, using every precaution, and see that we have a serviceable tool as soon as possible." About an hour later Pat showed the most beautifully tempered tool one ever laid eyes on. But upon examination with a good, sharp file, we found that the tool had never been hardened. To prevent cracking Pat simply had tempered it, that is, colored it. He had not hardened the tool before he attempted to temper it.

### *Hardening and Tempering a Cold Chisel*

A cold chisel is a very much used and often a very much abused tool. The regular practice after hardening is to heat a small portion of the blade end and dip the smaller portion in water, then polish the cold surface and allow the heat to travel at a high rate of speed toward the point, tempering by color of the oxide formed thereon.

The writer spent about three months investigating the causes for failure of chisels and their inefficiency. Good practice is to make the blades thinner in proportion to the size and type of work the chisel must cut, then heat the chisel the full length of the blade and quench for some time. The tool is taken out of the liquid so as to allow sufficient heat in the shank of the tool that the heat may travel at low speed toward the cutting point and produce the desired dark blue tempering color. The slower the temper color travels toward the point and the more uniform the color appears the full length of the blade, the longer the life of the tool.

The advantages of full length tempering may be demonstrated by making a tool maker's chisel from  $\frac{5}{8}$ - or  $\frac{3}{4}$ -inch octagon stock with a blade about  $\frac{1}{8}$ -inch wider than the stock and about three and a half or four inches long. Reduce the back end of the blade to about  $\frac{3}{16}$ -inch or less and the points to about  $\frac{1}{16}$ -inch. After forging the chisel, anneal it to remove all forging stresses, and heat the chisel through the full length of the blade and up part of the handle or shank. Quench bodily until one is sure the

entire blade is cold, but allowing some heat in the shank for removing any hardness at the junction of the blade and handle, that may have been caused by quenching. Polish the flat side of the blade. Select a piece of iron about  $\frac{1}{2}$ -inch thick by  $1\frac{1}{2}$  inches wide, heat to a red heat and if the temper has not appeared in the shoulder of the blade, apply the hot iron edgewise until the back end of the blade turns blue, moving the hot iron forward but always ahead of the color so that one may get a uniform temper color throughout the entire length of the blade. Such a tool will last a good toolmaker for several weeks.

### *Tempering of a Punch*

Many punches are inefficient because in tempering, a distinct line of demarcation is created just below the point between the tempered and soft steel. Make a punch regardless of size, then anneal it to relieve stresses. Reheat above the critical temperature for a distance of about  $\frac{2}{3}$  or  $\frac{3}{4}$  of its length from the point towards the head and quench it in water until nearly cold, leaving just a little heat in the head end of the punch. Polish a small space full length of the punch and hold it over a gas flame or a forge fire and draw the color on the heavy end first, until the blue appears and disappears on the polished surface. Continue this process towards the point and when the color is uniform throughout the mass, dip it in the water for a second or two to stop the tempering action. Then let it cool slowly. A splendid test for such tools is a good, sharp file. The file must cut from one end to the other, even including the point of the punch.

To demonstrate the value of this method of tempering, clamp the head end of the punch in the vise with the tapered part of the punch extending above the vise jaws. Strike it lightly with a hammer, and then try to bend or break it. Continue the experiment until you develop the kind of a punch desired, one that you cannot bend or break with reasonable effort. A more severe test is to drive the punch through a block of soft steel as shown in Fig. 141. This type of tool may be made in mass production by tempering in bulk at a temperature that will develop the characteristics desired.

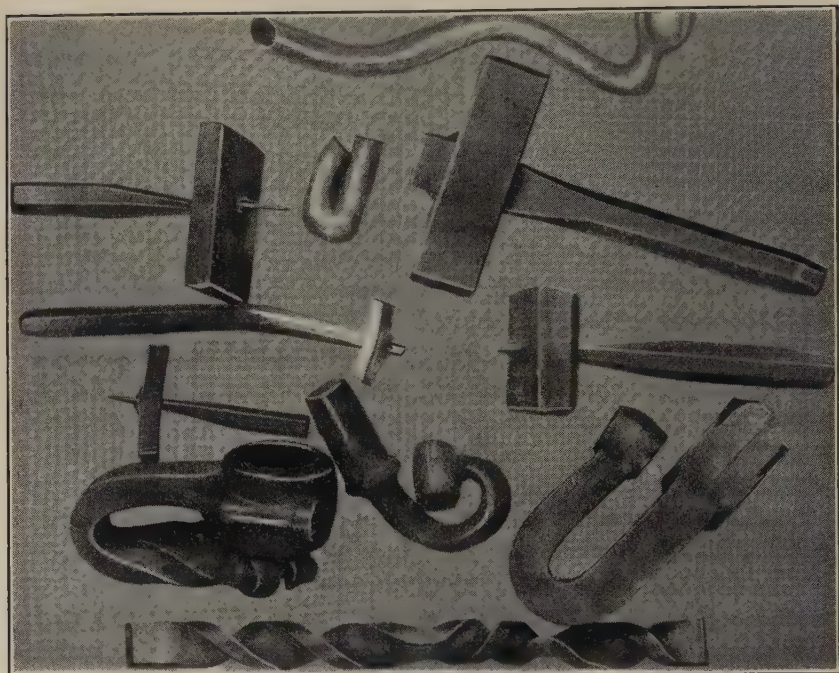


Fig. 141—Showing Properly Hardened and Tempered Tools and Punches.

### *Tempering Large Masses of Steel*

We are indebted to the scientific application of this method of treating steel for developing real fatigue resisting materials in our present high powered automobiles and reciprocating parts of power transmission machinery. When properly hardened in oil or water, the parts are tempered or "drawn back" by reheating to various temperatures from 900 to 1200 degrees Fahr., depending upon the physical characteristics desired. The object is to change the microconstituents from martensite or troostite to sorbite. Sorbite is very tough.

Large and costly installations of electric and oil heat treating furnace units are regulated by clock mechanism and automatically controlled by pyrometers. Automatic conveyors carry the material from the hardening furnace to the tempering furnace with the human element practically eliminated. Fig. 142 represents such an installation from which 6000 pounds of ma-



Fig. 142—Automatic Electric Heating and Tempering Furnaces with Mechanical Quenching Device for Heat Treating Automobile Crank Shafts. This Installation Handles 6000 Pounds of Metal Per Hour.—Courtesy Geo. J. Hagan Company.

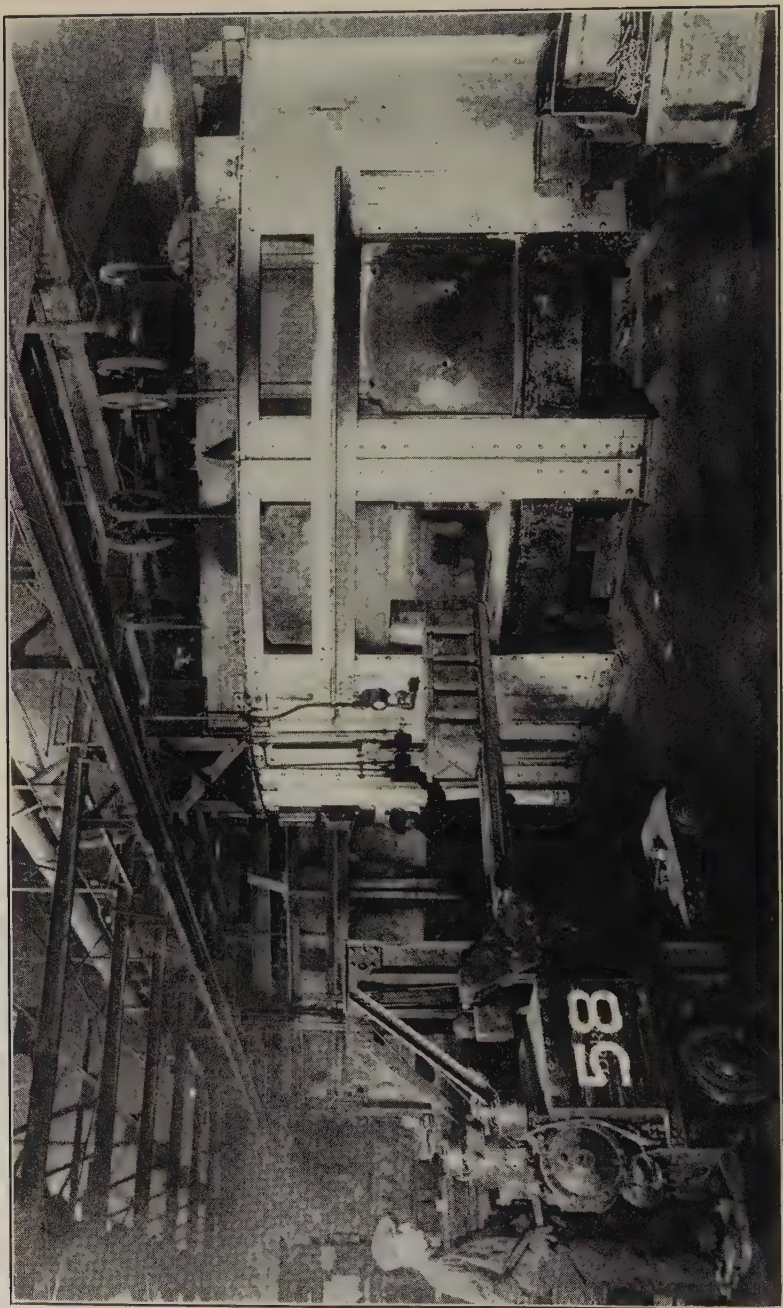


Fig. 143.—A Large Carburizing Furnace Being Loaded.—Courtesy Geo. J. Hagan Company.

terial per hour are produced on an average cycle of 45 seconds, i.e., a piece is quenched every 45 seconds.

In determining the serviceability of the material there must be a proper combination of physical characteristics, strength, hardness, elongation, and reduction of area to eliminate failure. These properties indicate the serviceability of steel. Hardened steel develops maximum strength with the loss of the last two factors, and these two factors are imparted to steel by proper tempering to promote the formation of sorbite.

Castings and forgings weighing several tons each are treated in the same manner as the smaller automobile forgings. Quenching is usually confined to air cooling. Tempering is often conducted in the same furnace that was used for heating to above the  $A_3$  temperature range.

#### CARBURIZING AND CASE HARDENING

Surface carburizing of iron is one of the oldest known arts of steel making. This was fully explained under the "Ancient Method of Carburizing Wrought Iron" and later under the cementation process. In fact, our present methods of case carburizing have been developed from the cementation process. The mechanism by which the product of charcoal, coke, charred bone, or other carbonaceous material enters the iron has been more or less of a mystery until recent years. The efficiency of the process depends upon a chemical reaction which takes place in and surrounding the material while in a heated state. Iron or low carbon steel parts or tools to be carburized are packed in an iron box in such a manner that none of the pieces touch each other or the sides of the box. Before closing the lid a sufficient amount of carburizing compound is placed on top of the parts. The lid is then sealed with clay to prevent the escape of gases from the box. Fig. 143 shows a large carburizing furnace being charged.

When the contents of the carburized box are heated to the proper temperature for carburizing, the heated carbon generates a gas that enters the steel and combines with the iron or steel parts. To produce these results, the contents of the pots must be heated above the  $A_{c_1}$  point indicated in Fig. 79 but usually to 1700 or 1800 degrees Fahr. At this temperature the gas forms and being under a slight pressure, it is probably forced into the steel. Upon

making contact with the steel, the gas decomposes, and drops its carbon which is then taken up by the iron. This process continues, the carbon going deeper and deeper into the steel.

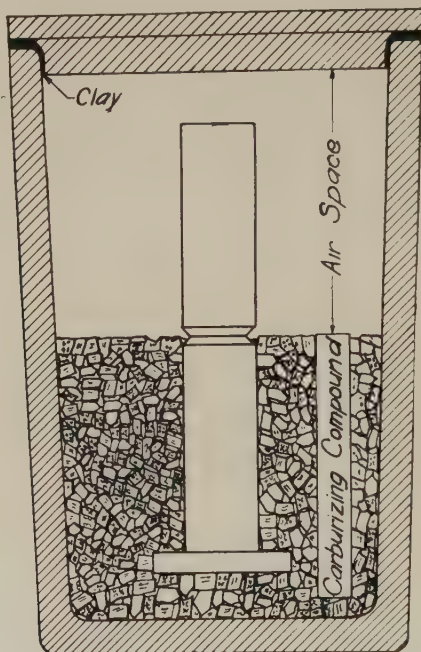


Fig. 144—Setup for Demonstrating the Effect of Air in a Carburizing Box While at Carburizing Temperature.

In successful pot carburizing it is important to surround the parts with carburizing compound, particularly on the top of the pot, to prevent any air seeping in through the clay-sealed cover. If air should enter, the opposite reaction takes place, and the metal will be decarburized. It is generally understood that it is a gas that carburizes. The gas is carbon monoxide, formed in combustion with lack of air (oxygen) in the sealed pots.

A simple suggested experiment to demonstrate carburizing is illustrated in Fig. 144. A notched piece of round low carbon steel is imbedded in the carburizing compound up to the notch, leaving an air space as indicated. If air or oxygen seeps in, carbon dioxide will form. During this reaction part of the carbon-

aceous material will actually burn. The surface of the steel in the projecting part of the rod will be decarburized by removal of the carbon from the steel.

Two homely illustrations may clear this point. On starting your automobile on a very cold morning, it is necessary to use the choke freely. In doing so, carbon monoxide gas passes off through the exhaust pipe which, as everyone knows, is poisonous and dangerous to health. If one places his hand over this exhaust pipe, the gases in contact with the hand will decompose and form a fine soot. That is a crude illustration of decomposition of carbon monoxide gas in the reaction that takes place in the carburizing process.

It is also well known that if a furnace fire is banked too closely without allowing for the escape of the resulting carbon monoxide gas, the home will soon be filled with this poisonous gas. By opening the draft in the morning and allowing free air or oxygen to enter the furnace, the reaction is just the opposite. The air in contact with the heated carbon forms carbon dioxide. From these two crude descriptions you will perhaps have a better idea of what takes place in the carburizing process. The formation of carbon monoxide is expressed by the following chemical equation:

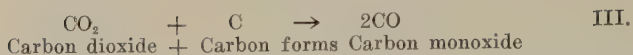


If there were sufficient air in the carburizing box the carbon would burn to form carbon dioxide ( $\text{CO}_2$ ) but since there is always an excess of carbon, the gas formed is largely carbon monoxide ( $\text{CO}$ ).

It seems probable that the carbon monoxide gas penetrates a short distance into the steel. The steel absorbs carbon from the gas according to the following equation:



The carbon liberated by the above equation is probably yielded in such a fine form that it can be dissolved by the solid steel. (The finest carbon powder visible to the eye is much too coarse to dissolve into solid steel.) The carbon dioxide produced by this reaction, on coming into contact with the large amount of hot carbon particles in the carburizing box, is again converted into carbon monoxide according to the following equation:



It will be noted that equation III is just the reverse of equation II. That is, carbon monoxide and carbon may unite to form carbon dioxide, or carbon dioxide may decompose to form carbon monoxide and carbon, depending upon the conditions. This is what the chemist calls a reversible reaction and may be written as follows:



### *The Effect of Temperature Upon the Carburizing*

The temperature must be sufficient to cause the surface layers of the steel to absorb carbon. Carbon does not seem to dissolve readily in steel unless the temperature is raised above the critical point, at which point there may be some absorption of carbon due to the transformation of pearlite to austenite. The action would be unduly sluggish. The higher the temperature the greater the solubility of carbon in iron. Carburizing temperatures vary from 1600 to 1800 degrees Fahr. The penetration is more rapid and the carbon content increases on the surface of the steel, but at the expense of grain growth as indicated in Fig. 79. As stated, at a temperature just above the critical range  $A_{c3}$ , carbon penetrates into steel rather slowly, requiring considerable time for a definite depth of case. It is therefore necessary to reach a compromise between two factors, temperature and time. An increase of temperature some distance above the  $A_{c3}$  point to 1650 or 1750 and even 1800 degrees Fahr. will produce a thicker case with richer carbon on the surface and in a shorter length of time but at the expense of large grain growth.

With these points in mind, the best method of determining under local conditions the factors temperature, time, etc., would be to carry out some experiments on various samples of steel, using the carburizing compound at hand, with the furnace and other equipment available. Experimentation will furnish fairly definite information of what to expect. This suggestion is made because of the many carburizing compounds on the market and the variation in heat treating equipment and personnel that may be controlling the operation. The experiments may be carried out along

the same line that we suggested for determination of the critical temperatures of steel by the fracture method, Fig. 107.

Another important factor to be considered is the richness of the carbon in the surface layers. If the material is to be case hardened without a grinding finish, it is desirable to have the carbon percentage in the outer layer about 0.90 per cent. As previously stated, this percentage of carbon in steel will develop almost the maximum hardening power. If, however, we anticipate removing ten to twenty thousandths for correct finish, it is essential that the outer layer be much richer in carbon so that the finished surface will contain about the correct proportion of carbon to

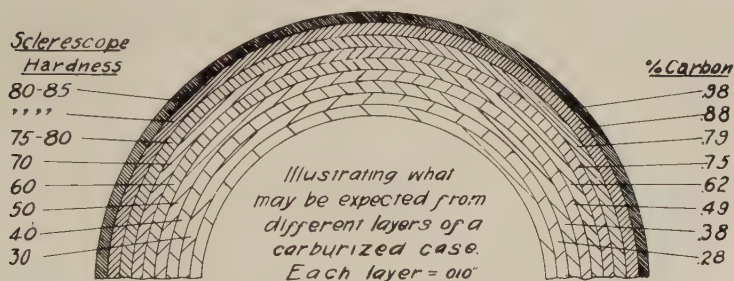


Fig. 145—Illustrating the Various Layers or Zones of a Carburized Round.

develop maximum hardness. If the outside layer is not rich enough in carbon and an excessive amount of stock is removed by grinding, the next layer being lower in carbon will not develop the maximum hardening power. In order to picture this point the drawing, Fig. 145 is introduced.

In standardized practice every factor that enters into the development of good carburizing practice is determined by many experiments and tests. The factors involved are selection of the proper type of steel, carburizing material, method of packing, heating cycle, temperature and time factors, and cooling process. Large and expensive equipment is installed, particularly in procedure control plants, whereby tons of material are scientifically treated with exact duplication. Fig. 143 shows a typical installation.

By comparison one will be interested in a case involving the carburizing of reciprocating parts in a railroad shop. In carburizing reciprocating parts for a locomotive such as links, pins, bush-

ings, etc., a large box was made by welding heavy boiler plate. The box was 15 inches high, 24 inches wide and about 5 feet long. The carburizing compound consisted of granulated charcoal and salt, mixed in the proportion of nine scoop shovels of charcoal to one shovel of salt. On the bottom of the box was placed about an inch and a half thick layer of this compound. The heavy links were placed carefully in the center and the smaller pins and bushings were piled on the outside with some of the smaller parts placed between the links. A layer of charcoal was then placed on the top and another row of material started and continued to within about three inches of the top. This space was filled with carburizing compound to within a half inch of the top. Next, a mass of fireclay in a pasty state was deposited inside, all around the edge. The lid to fit the box consisted of a half-inch boiler plate forced in and pounded down into the clay to seal the contents. The furnace used for heating the box was a large coal-fired forging furnace used daily in the heavy forging work. Directly after the last forging heat was drawn for the day the box was rolled in on bars of round iron used as rollers.

The night watchman acted as fireman, in addition to his regular duties. Intermittent firing naturally caused a fluctuation of temperature. With no temperature measuring device except the eye, the box was just heated to a good cherry red or yellow heat, hoping that the box at least would not burn. Just previous to the forge men coming to work in the morning the box was rolled out, the lid removed and these parts were quenched in water direct from the box.

Examination of the contents showed that all pieces close to the edge of the box were highly carburized, with exceptionally coarse crystalline structure in both the case and core. The heavy material in the center showed only a slight carburization. It may be noted that the penetration of carbon was just the reverse of that desired. The thin bushings, pins, etc., should have been slightly carburized, and the heavy sections carburized deeply. Such conditions clearly illustrate the necessity of standardized practice and in particular the importance of having individual boxes for definite sizes of work, and a time-temperature factor for each size.

Let us now attempt to study the effects of quenching carburized material. It would be well to remember, we are dealing with

two distinct types of steel, the core and the case. The core consists of a soft steel, usually containing less than 0.20 per cent carbon, and possibly some alloys such as, nickel, chromium, vanadium and molybdenum. The case is in reality a high carbon tool or high carbon alloy steel depending upon analysis. In procedure controlled plants carbon in the outer case will range from 0.90 to 1.00 per cent or more, depending upon the carburizing temperature, speed of carburizing, material, etc. If the temperature in the material reached 1800 to 2000 degrees Fahr. as in the railroad shops, two things would happen. First, carbon in the case would be very high as indicated above the hypereutectoid side of Fig. 79. Secondly, grain growth would take place both in the core and in the case, as illustrated, the portion above the  $A_{cm}$  line in Fig. 79.

### *Quenching from the Pot*

Quenching such material direct from the pot or box, prevents the free cementite from separating out in the case, as indicated in the hypereutectoid side of Fig. 79. This develops an exceptionally hard case but at the expense of a coarse granular structure. We will follow what happens in the core. You may note that quenching retains the carbon in solution but makes a hard and brittle core. The grains are large, being formed by holding the material at a high temperature for considerable length of time. Where strength of the material is less important, this single treatment will answer the purpose, but it would be a crime to place such material in service where there is excessive alternating action.

To reduce the undesirable conditions of the metal, regulate time and temperature to produce the desired result, then as for other steels, there are several standard processes of heat treatment. First, draw the pots from the furnace and time-quench the material through the critical range only, for the specific purpose of retaining the carbon in solution both in the core and in the case, and immediately reheat to refine the core. Where production methods will allow this procedure, much time and energy may be saved by this practice and there will be less warpage of the material. However, it must be certain that the metal is cooled down below the recalescence point, 1290 degrees Fahr. The next step is immediately to place the material while hot in a hardening furnace and heat above the  $A_{c1}$  point, to develop fine grain struc-

ture in the case and therefore maximum hardness because of the retention of free cementite in solution. On the other hand, heating the core above the  $A_{c1}$  point softens any hardened portion produced by the time quench. This heating does not change the structure of the core, except to soften it. The changes that take place both in the case and core are clearly illustrated in Fig. 79.

A study of this figure should convince one that no excessive hardness can be retained in the core, due to the fact that time quenching through the critical range from above the  $A_1$  point retains the carbon in solution and owing to the slight amount of carbon present (0.20 per cent carbon) it cannot develop hardness to any appreciable extent.

The most widely used practice is to allow material to cool to atmospheric temperature in the pot. Let us now turn to drawing, Fig. 79, and study the changes that take place on the cooling of the two grades of carbon steel. The grains developed at carburizing temperature will not be any smaller than when cooled to atmospheric temperature in the pot. Two important things happen. On cooling to the  $A_{r1}$  point austenite changes into martensite, troostite, sorbite, or pearlite. If the case is rich in carbon, the free cementite in the iron containing about 0.90 per cent carbon will be rejected in cooling through  $A_{r1}$ .

If such steel is reheated to above the  $A_{c1}$  point to develop a hardened case, pearlite of the core changes to austenite as indicated by the black spots in the drawing. Examining the change in the case, it will be noted that the pearlite within the grain boundaries of free cementite changes into a fine-grained austenite, leaving the free cementite on the surface. This being true, we could expect a chippy and flaky case. In other words, a rupture might follow along the path of the free cementite of the grain. This is not at all desirable, particularly, if the carbon indicated exceeds eutectoid ratio (0.90 per cent). On the other hand, if the ratio in the case does not exceed nine-tenths of one per cent this method may be used advantageously giving a fine-grained and hard case with a moderately coarse-grained but tough core.

The rejection of massive cementite can be corrected by normalizing at above the  $A_{cm}$  temperature, followed by quenching. The core and case are then refined by what is termed a double treatment. Reheat after time-quenching or pot-cooling to 1550 to 1575,

or even 1600 degrees Fahr. The usual procedure is to quench in oil from this temperature. A fine-grained structure is developed in the core, and the carbon is in solution. At this temperature the carbon of both case and core is thrown into solution but the grains in the case grow larger. Quenching retains these characteristics. Reheat to 1400 to 1450 degrees Fahr. and quench in oil or water. This is for refining the case. Refer again to Fig. 79. This temperature range is just above the  $A_{c1}$ . At this range the grains in the hypereutectoid case grow smaller and smaller. The fine grains in the low carbon zones remain undisturbed. The quench retains these conditions. Tempering at 250 to 500 degrees Fahr. relieves all quenching strains, and toughens the zone between the core and case without seriously reducing the hardness of the outer case. This "double treatment" is an ideal way of treating all carburized work. It is expensive and can only be used for parts undergoing severe service where maximum hardness of the case and maximum toughness of the finished product are essential. Automobile clash gears where made of carburized material furnish a good example of parts that should be given this double treatment.

The question now arises as to why such material is quenched to atmospheric temperature and again reheated. The quenching in this operation is not for the purpose of creating hardness. It is purely for the purpose of preventing a separation of free cementite or the separation of austenite in the core, most of which is accomplished if the metal is time quenched to just below the critical range. This being true, why remove 1200 degrees of heat, causing considerable warpage and the possible cracking of the surface by too sudden application of heat when again reheated?

If such material is quenched to below the  $A_{r1}$  point then reheated above the  $A_{c1}$  point, the physical structures will be the same as though the metal had been quenched to atmospheric temperature. It may again be reheated to the  $A_{c1}$  point and then quenched drastically in water to induce maximum hardness of the case and a fine grain structure both in case and core.

There has been considerable complaint that double treatment has a tendency to form more or less of soft skin. In most cases this is due to the furnace atmosphere being oxidizing during the several reheatings. Care in the control of atmosphere and temperature and proper methods of quenching will greatly reduce, if not

prevent, such a condition. The furnace atmosphere should be slightly reducing at all times.

### *Gas Carburizing*

In carburizing steel by this process it is heated to the desired temperature, usually in a revolving steel retort, sealed to prevent the escape of gas. When the metal attains a definite temperature some gas such as carbon monoxide, methane, city gas or natural gas, is passed through the retort. Under proper conditions the surface of the steel absorbs carbon from the gases, the same as in pot carburizing. The quality of work produced by this process depends largely upon the character of the steel, the composition of the gas, the uniformity of temperature of the retort, the time of exposure and the volume and pressure of the gas.

### *Cyanide Hardening*

Cyanide is known as liquid carburizer, and includes sodium cyanide and potassium cyanide or mixtures of these chemicals. There are two general methods of using these chemicals. First, the cyanide is heated in a pot to a temperature well above its melting point and the parts to be hardened are immersed in the molten cyanide for a definite length of time until a case of the desired depth is formed. The carburized parts as a general rule are quenched immediately on removal from the pot. This method is used chiefly for producing a very thin case. Uniform thickness of case can only be developed when sufficient space is allowed between the parts suspended in the liquid so it will flow freely between them and uniformly heat each part. For convenience in handling, small parts such as pins, bolt, nuts, washers and bushings are put into a specially designed wire basket. The basket and its contents are immersed in a liquid solution. It is assumed that the liquid cyanide will immediately circulate through the mass. It does so to a certain extent, until the liquid freezes by contact with the cold material which lowers the temperature of the liquid, therefore it freezes and becomes a solid. Investigation of this point demonstrated that with a small basket containing seven pounds of pins, it took eleven minutes to dissolve the center of the frozen mass, with the result that those pins on the outside

of the basket reached temperature first and were carburized. A period of 25 minutes was allowed for the basket of material to carburize, so one can readily account for the variation in hardness and depth of case. Provision should be made for all parts to heat at the same time. This may be accomplished by making a basket or a sieve composed of a band of iron in the form of a ring somewhat smaller than the dimensions of the pot. To the bottom, fasten a wire screen like a sieve. The basket can be suspended in the pot.

When ready to load, immerse the receptacle in the heated metal and allow it to heat through. Select a small scoop shovel to lift the cold parts and then drop them into the receptacle through the cyanide, in other words, shift them about in the basket, regulating the speed of carburization and loading in such a manner that no freezing takes place.

Where only a few pieces are to be treated, it may be done in a forge fire by heating the part. The cyanide in powdered form is sprinkled on the hot steel, or it may be dipped into the powdered cyanide held in a container. It is then put back in fire and heated to a good red heat and quenched. If one desires a little thicker case, the operation is repeated by adding more cyanide to the heated material. This method is used by blacksmiths and toolmakers in order to locally harden some soft piece of steel.

## ALLOY STEELS

The definition of alloy steels as adopted by the International Association for Testing Materials is as follows: "Alloy steel is steel which owes its distinctive properties chiefly to some element other than carbon, or jointly to such other elements and carbon. Some of the alloy steels necessarily contain an important percentage of carbon, even as much as 1.25 per cent. There is no agreement as to where the line between alloy steel and carbon steel shall be drawn." Alloying elements have a marked influence upon the physical properties of steel. Each alloy imparts some distinctive property such as greater depth of hardness or retention of fine grain structure by retaining the carbon and other alloying elements in a finely divided state. Some alloys prevent or retard grain growth. Due to these properties we can expect greater

strength and fatigue resistance when alloy steel is correctly treated.

It is unfortunate that some designers are of the opinion that because alloys are added to iron, they impart their distinctive characteristics to the steel as it comes from the mill or the forge shop. Alloy steel should always be heat treated before it is put in service. There is, however, some benefit to be derived from raw or annealed alloy steel as compared with carbon steel, but the benefit is not commensurate with the increased cost. In a heat treated condition there is a very marked improvement in its physical characteristics.

The alloying elements also have a very marked influence upon the critical temperatures. In some alloy steels the  $A_{c_3}$  occurs at a much lower temperature than in plain carbon steel and some alloys such as manganese, depress the  $A_{r_3}$ . Chromium, vanadium and molybdenum raise the  $A_{c_3}$  transformation. Several alloys are often used in the same steel, each exerting some beneficial influence. To those interested in any particular kind, type or treatment of steel the author suggests consulting any standard text book or handbook such as that of the American Society for Steel Treating, but the author wishes to touch on two steels at this time.

#### HARDENING AND TEMPERING OF SPECIAL STEELS

Heat treatment of the usual alloy and special tool steels is fairly well established. In using new alloy or tool steels the writer advises following instructions furnished by the company manufacturing the material, at least until it has been given a thorough trial. Various treatments may then be tried.

##### *Annealing After Forging*

Annealing imparts uniformity of structure throughout the steel. *Heat slowly and uniformly* because the fine grained and dense alloy steel is very sensitive to heat changes. The object in slow cooling is to prevent surface hardness. There is danger in cooling too rapidly, thereby setting up internal stresses in the metal which the process of annealing attempted to remove. Temperature differences between the furnaces and the non-heat conducting material into which the steel is to be buried and the possibility of chilling the surface by immersion into such material should be

considered; therefore, furnace or box annealing would be desirable as a preventative method. In reheating for quenching or tempering, heat slowly and uniformly because the absorption of heat from the surface to the center of the steel seems to be very much slower than with ordinary carbon steel.

### *Quenching*

If you have performed the experiment suggested of quenching two similar blocks of carbon and oil treated steel, it may be noted that carbon steel becomes somewhat shorter because of drastic quenching, upsetting or shortening its length and due to that inherent quality in that type of steel there is very little danger of surface rupture by such quenching provided that internal stresses are quickly removed by tempering. In the quenching of oil hardened steel the resistance of the hot center to distortion would cause surface rupture by drastic quenching of such material in water, etc. On the other hand, alloys lower the critical points and give sufficient time to secure reasonable depth of hardness by quenching in oil.

### *Non-Deforming Steels*

The term non-deforming steel often leaves the impression that steel does not shrink or contract. According to the laws of physics, when heat is applied to a mass, it expands; and if heat is withdrawn from that mass, it contracts to its previous dimensions. The difference between non-deforming steel and carbon steel is that when heat is applied to carbon steel it expands to a little greater extent than non-deforming steel. When quenched, carbon steel deforms and becomes shorter in length than the non-deforming steels.

Non-deforming steel may be quenched in oil with but very little deformation in the portion of the steel that cools last. A similar tool, jig or die made of carbon steel will be markedly deformed in the portion of the metal that cools last. The following simple experiment may be of interest. Select a piece of carbon tool steel, and a piece of non-deforming oil-hardening steel, each of the same size. Check the sizes with micrometers, heat, and quench as directed in the regular practice for both types of steel. Repeat the heating and quenching a number of times, recording the results. At the completion of this test you will find that the

carbon steel block is much shorter in length than the non-deforming type of steel.

### HIGH SPEED STEEL

The term "high speed steel" implies a steel with the ability of working at faster cutting speeds, handling deeper cuts of metal and removing more stock than other tool steels. The term is broad and includes varied analyses, but is usually associated with cutting steels in which tungsten is the important element. As a rule the higher tungsten steels are used for heavy cuts and the lower tungsten steels are used for finishing operations in which the cuts are lighter, but in which high machine speeds are desired. Finishing steels of this type are often referred to as semi-high speed steel. The finishing steels are usually characterized by higher carbon and lower tungsten. Table III shows three analyses of typical high speed steels. In this lecture, we shall consider only the 18 per cent tungsten steel, the first shown in Table III. The same general ideas are common to all the high speed steels, but reference should be made to the literature, steel companies' recommendations and handbooks such as that of the American Society for Steel Treating, before adopting a certain type of steel for a specific job.

**Table III**  
Analyses of three types of tungsten high speed steel are:

Tungsten Per Cent	Carbon Per Cent	Chromium Per Cent	Vanadium Per Cent
18.00-20.00	0.60-0.75	3.50-4.00	0.60-1.00
16.00-17.00	0.60-0.75	4.00-4.50	1.50-2.00
13.00-14.00	0.60-0.75	3.50-4.00	1.00-1.50

In removing large quantities of metal, the cutting tool becomes very hot, often working at a red colored heat (around 1000 to 1200 degrees Fahr.) The tungsten, chromium, vanadium and carbon form complex carbides. When heated to 2250 to 2400 degrees Fahr. these carbides are dissolved and upon quenching from these temperatures austenite is retained. Some carbide is precipitated, but is usually, and should be, uniformly distributed throughout the steel. On tempering after quenching, secondary hardness is developed. This is an important characteristic of high speed

steel as it is due to this hardness that high speed steel maintains its cutting ability at temperatures and speeds far in excess of other cutting tools.

Before forming a high speed steel tool, the steel should be annealed to impart small and uniform grain size. The steel should be annealed by heating uniformly to about 1600 degrees Fahr., and should be soaked until all the metal has attained that temperature. It should then be slowly cooled in the furnace, lime, ashes, etc. until cold. Slow and uniform heating are especially important in high speed steels because the material is very brittle and small internal ruptures can easily be caused by nonuniform heating. An internal rupture almost invariably results in tool breakage. After the tool is formed by machining or grinding, it is heated to 2250 to 2400 degrees Fahr., soaked to insure the solution of all carbides, quenched, and tempered to relieve quenching strains and to develop secondary or "red" hardness.

It is important to take two distinct steps in heating to the high temperature. The first step, usually called preheating, consists of very slowly and uniformly heating the tool to about 1500 degrees Fahr. Damaged tools are often traceable to rapid preheating. From about 1500 degrees Fahr. the tool should be heated rapidly to 2250 to 2400 degrees Fahr. and held at this temperature for sufficient time to dissolve the carbides. The more intricate tools that are not ground after treatment are heated to the lower temperature. As the high quenching temperatures are near the melting point of the steel, great care must be exercised to prevent blistering or "burning" of the tools, particularly those tools of small and intricate shape such as threading tools, reamers, etc. Since these high temperatures cause excessive grain growth, tools should not be held at temperature for a longer time than is necessary.

High speed steel may be quenched in air or oil from the hardening temperature. Lead is sometimes used for quenching the more delicately shaped tools. In oil quenching, the bath should be held at 150 to 200 degrees Fahr. to guard against the possibility of breaking intricately shaped tools. Tempering relieves quenching strains and develops secondary or "red" hardness. After tempering at 1050 to 1150 degrees Fahr. the tools should be cooled in air.

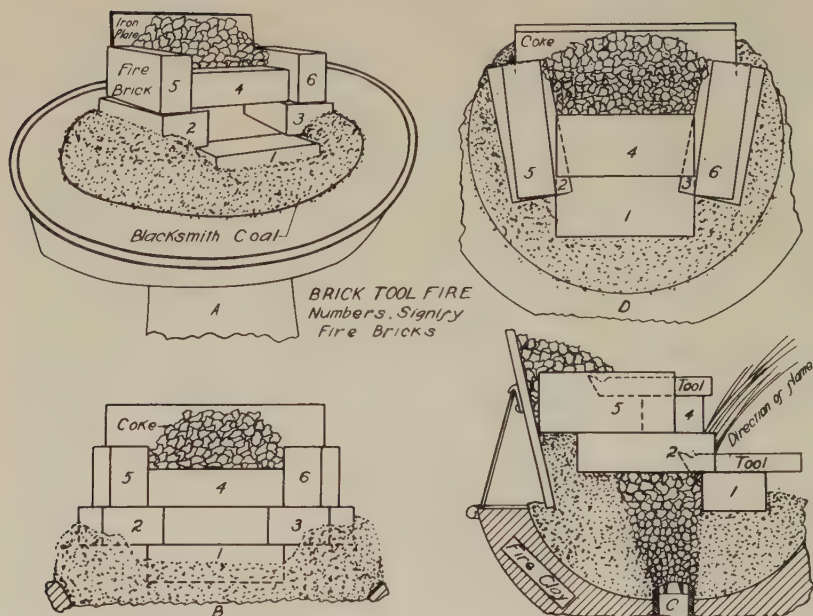


Fig. 145a.—Showing an Open Forge Fire for Hardening High Speed Steel Tools.

### *Hardening High Speed Steel in an Open Forge*

The drawing, Fig. 145a, is a suggested tool dresser fire, simple to construct, requiring only 6 fire bricks and a plate of iron as indicated at A. It has been found very efficient for heating the ends of tools such as lathe tools, chisels, punches, etc. for forging or hardening purposes. It has considerable advantage as a preheater. Place the cold tool on top of brick 4 as at C. It is also advantageous in keeping some of the heat in forged tools previous to reheating for annealing or hardening.

The bricks are placed in the opening or door of the fire so as to produce maximum heat from the bed of fuel. Brick No. 4 acts like a hot arch in a furnace by preventing the flame blowing directly onto the tool. Hard Coke is more desirable for the intense heat required in heating high speed tools for hardening.

This is the type of fire the writer often uses where a regular high speed hardening furnace is not available for demonstrating

the advantages of heating high speed tool steel to a high temperature or sweating heat. With such a forge fire the heated tool does not come in contact with the hot coke.

It is important to carefully place bricks 1 and 4 as shown. Preheated coal or coke at the top of the hopper should be used for replenishing the hot fire. The tool is placed on top of brick 4 for preheating, and moved to brick 1 for final heating.

## LECTURE VI

### WARPING, CRACKING AND SHRINKING OF STEEL

In the foregoing lectures, reference has frequently been made to the distortion, warping and cracking of steel. This lecture will show their causes and the effects in service. The distortion, warping or cracking of metal is a serious and costly problem in metal trade industries. Figs. 146 and 147 show a few problems that occur in all metal producing plants. These problems are presented at this time with the hope that the readers may study and deduce the answers for themselves and to see if the readers and the writer agree as to the cause. The writer believes that localized heating or localized cooling causes distortion, that distortion causes warping, that warping creates strain and that strains finally cause cracking.

When heat is applied to metal, it expands in length and other dimensions. When steel is heated above the critical temperature this expansion is about  $\frac{1}{8}$  inch per foot. It is generally understood that when metal is heated and slowly cooled, it contracts to its previous size.

In the preceding subject matter the caution has often been repeated to heat slowly and uniformly. Every precaution is often taken in the production of finished metal parts to produce parts that are free from all stresses and in perfect alignment to even within 0.001 inch or better. Quite often, material is thrown carelessly into a furnace with the hope that it will heat slowly and uniformly and come out of the furnace perfectly straight. It comes out straight only when the metal has been uniformly heated throughout.

An ideal method of heating is to use a vertical cylindrical shaft furnace in which the flame can circulate completely around the work. The metal can be heated slowly, depending upon the intensity of the flame. The work must be placed upon a pedestal, or otherwise supported from the bottom of the furnace, and it should be so placed that any unsupported lengths do not exceed the ratio of at least 4 to 1, length to diameter. When supported in this manner it can be heated to the proper temperature without danger of distorting or warping. When a piece of steel, such as

a large shaft, is placed vertically and heated, the unsupported length should not exceed four times its diameter or the piece may bend due to column weakness.

Some time ago, the writer had the pleasure of witnessing the heating of a large gun in a United States ordnance factory. Picture a cylindrical shaft furnace about 70 feet in depth. A traveling crane above the furnace lifted the gun, lowered it into the furnace and held the gun during heating, to prevent column action.

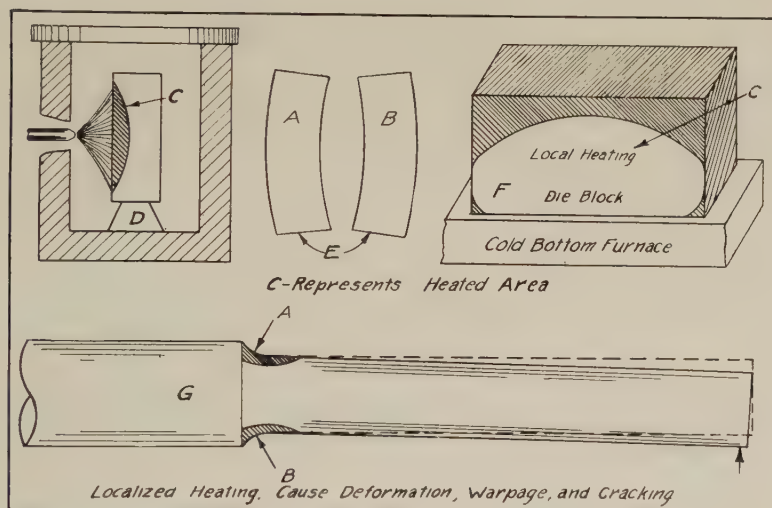


Fig. 146—Sketch Illustrating the Causes of Warping and Cracking of Steel.

When uniformly heated, the gun was lifted out of the furnace, conveyed to a vertical cylindrical tank about the same depth as the furnace, and quenched perpendicularly.

From this example the reader may realize the importance of properly supporting material when it is heated in a horizontal rather than a vertical position, and the importance of elevating the material from the bottom of the furnace to afford an opportunity for uniform circulation of the heat. Some of the methods of heating in general use are diametrically opposite to the ideal conditions described above. Much material is bent or warped upon leaving the furnace.

The square block of steel shown at F, Fig. 146, is being locally heated on one side by the direct flame of an oil burner. The

heated area of the steel is indicated by C. If the application of heat is continued in this manner until the entire block is heated to a uniform temperature, the writer's conception is that the local heating will cause distortion and that such distortion will cause warpage. When cold the piece will be crooked.

The writer would like to have the reader answer the following questions for himself. When a block of steel is heated on one side as shown at D, will it bend to look like A, or will it resemble B?

What would be the effect of locally heating die block F as indicated by the heated area marked C? Will blocks D and F

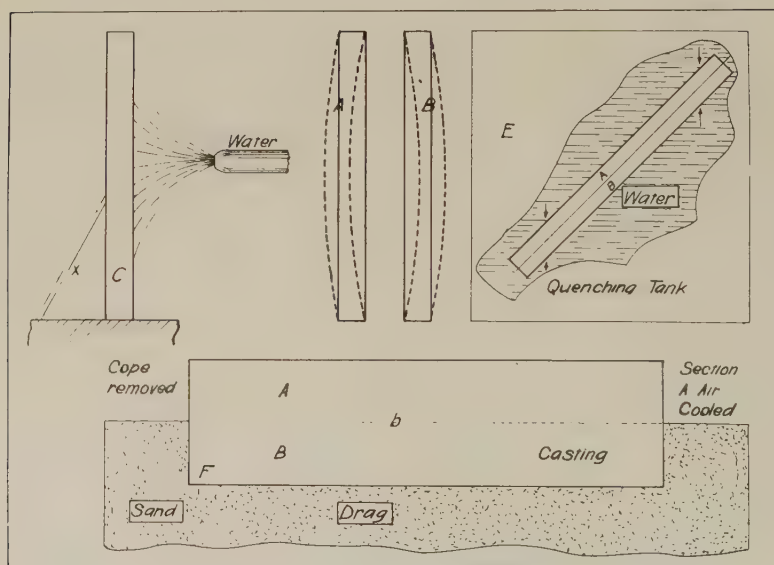


Fig. 147—Illustrating Warping and Cracking from Localized Cooling.

warp or crack when cold, particularly when quenched before local heating has extended to the whole block? At F the writer has attempted to depict the heating of a die block lying on a cold furnace bottom as is often done. If heated under these conditions, it would be impossible to heat uniformly because there is not opportunity for circulation of the heat around the block. The effect will be explained in detail later on.

You have decided in your own mind that local heating will cause distortion, but you may not be quite sure of the results. The next problem is the application of that principle to straightening shaft G. The shaft is shown slightly bent at the shoulder and the object is to apply heat and raise the point of the shaft to the dotted line, straightening it. Where should the shaft be heated in order to straighten it? At A or at B?

### *Deformation from Local Cooling or Quenching*

Fig. 147 shows distortion and warpage caused by localized cooling. It is assumed that the metal has been heated slowly and uniformly to make sure that no deformation was caused during heating. The question is: What is the effect of cooling one side of a plate of metal as indicated at C? This figure represents a heated plate of steel with a large stream of water being thrown on one surface of the plate, the stream of water to continue in this manner until the piece is cooled to atmospheric temperature. Which way will the metal be bent when cold, as shown at A or like B?

The next problem is one that occurs frequently in quenching cylindrical and long pieces. We are assuming that the metal being quenched in water at tank E has been properly heated to prevent distortion. The writer's contention is that if the metal is quenched vertically, flat side toward the water as indicated, it will be bent when cold. Which way will it bend, like A or like B?

The next problem is one that frequently occurs in the foundry, when warping is often attributed to shrinkage. The casting is a flat plate that is placed half in the cope and half in the drag. The thickness of the plate makes no material difference because the same action takes place in any similar shaped casting. The casting F has solidified in the mold, the cope is removed down to the dotted line "b", and section A is allowed to cool in the air, B remaining in the sand to cool slowly. When the entire casting is cold, which way will it bend, concave or dished side up toward A, or concave side down toward B? Your decision will undoubtedly be based upon the consideration that metal changes its length upon heating and cooling, consequently you may not consider the real factors. The following factors should be considered.

*Metallurgical and Mechanical Factors*

There are several metallurgical and mechanical factors that should be considered in their effect on cracking or rupture of iron and steel parts. From a metallurgical standpoint, external defects or discontinuities in metal will not grow in size until a stress has been applied to that part. Stresses may be created by localized heating or cooling or by tension or compression while the metal is in service. These stresses usually concentrate at weak points such as surface defects, or cracks, and cause rupture. Cracking and rupture which may take place while the piece is at the work shop and not under stress, must be traceable to causes other than force or pressure applied while in service.

The cause in the writer's estimation is strain set up by improper heating or cooling. Expansion or contraction places any defect under tension or compression and may result in failure.

1. All metals have a fairly definite strength at atmospheric temperature depending of course upon their chemical composition, freedom from defects, method of fabrication and heat treatment.

2. *Expansion.* It is a generally known fact that steel expands upon heating. To be accurate, it expands 0.0000065 inches per inch per degree Fahr., and when heated above that critical temperature this expansion amounts to about  $\frac{1}{8}$  inch per foot, so that nearly all metals occupy a larger space when hot, than at atmospheric temperature. It would be well to keep this thought in mind in the solution of many of the problems that follow.

3. *Strength of Metal at Elevated Temperature.* In general, it is thought that as the temperature of a piece of steel increases, the steel becomes weaker and weaker. Investigations referred to in a previous lecture have proven the contrary to be true up to some 400 to 600 degrees Fahr., depending on the analysis and treatment of the steel. Beyond this temperature, the strength decreases with the rise in temperature.

4. This loss of strength at elevated temperatures, and the accompanying increase in plasticity are utilized in the forging and rolling processes by heating the metal to a semi-plastic state which requires less power to roll, forge or upset the steel into various shapes. This weakness of metal at high temperatures is one of the important factors in the causing warpage and cracking.

5. *Resistance to Expansion or Contraction.* When a block of steel is heated, it expands in all directions in proportion to the increase of temperature. Likewise, if heat is removed from any part of the block, the block must contract. In the attempt of the locally heated zone of metal Fig. 146, to shrink or contract, consideration must be given to the resistance of adjacent cold metal which tends to prevent the heated metal from returning to its normal dimensions.

6. *Flow of Metal in a Semi-Plastic State.* It has been shown in previous lectures that when metal is heated and force is applied for forging or rolling that the metal will flow, following the path of least resistance. The flow of heated steel is important in considering the resistance of cold metal that is adjacent to the heated metal, preventing normal increase or decrease in dimensions.

7. *Compression in the Localized Cooling of Metal.* In discussing the cooling of block C, Fig. 147, we have not considered internal compressive forces. When the face of the block is cooled by the water spray, that side shortens its length and in attempting to return to its normal length at atmospheric temperature it puts much of the remaining hot metal under compression and shortens the length of the hot side as well as its own length. The hot side upsets somewhat and since it must shorten its length when cooled, it will be crooked or bent when cold.

8. *Column Weakness.* Another form of distortion is known as buckling or bending. Due to lack of strength in the cross sectional area the metal may be unable to withstand compressive force when applied. This is quite noticeable in thin sections.

### *Strength of Metal at Various Temperatures*

Fig. 148 shows the changes in the strength of the heated steel. The first part of the strength curve is a composite taken from the records of several investigations. The steel shown has a strength of 60,000 pounds per square inch at room temperature.

The strength of this steel remains fairly constant up to about 575 degrees Fahr. From this point, the strength increases somewhat up to about 700 degrees Fahr. From there on, the strength drops rapidly as the temperature is increased to the critical range at which point steel has a very low strength. The writer contends that steel is weakest when at the critical temperature and he

cannot conceive of the metal having any strength just as the larger grains are being reborn into small grains on passing through the  $A_3$  critical. Can we picture metal in the process of rebirth as having sufficient strength to sustain a load of even its own weight? The reason the steel does not fall apart or change its shape is due to the fact that the transformation is progressive from the outside toward the center, even in a fine wire. The curve is drawn to show the weakness of the metal in passing through the critical range.

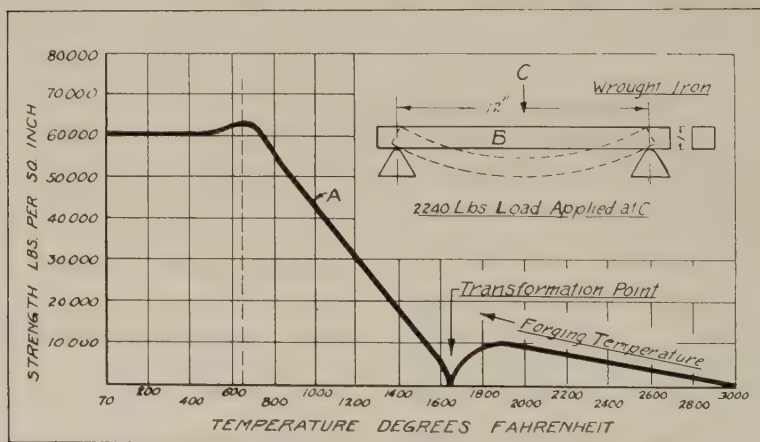


Fig. 148—Diagram Showing the Loss of Strength of Steel Due to Heating Temperature.

By following the curve, which is shown above in Fig. 148, it may be noted that with increase of temperature above the critical temperatures, the strength increases to about ten thousand pounds per square inch, and with further temperature increase it naturally becomes softer, weaker and more plastic up to its melting point.

To further emphasize the strength and weakness of metal, a 1-inch square piece of wrought iron supported on 12-inch centers as indicated at B will sustain a load of about 2240 pounds before bending or deflecting from a straight line. If this bar is heated to a white heat, it will bend of its own weight as indicated in the dotted line at B, Fig. 148. If the work is in a horizontal position while being heated, it should be supported to prevent the metal from finding the contour of the uneven bottom of the furnace.

*Demonstrating the Loss of Strength with Heated Wire*

To further emphasize the loss of strength of metal, refer back to the wire demonstration shown in Fig. 105. The wire used is a high carbon steel piano wire, having a strength of about 350,000 pounds per square inch. The wire is connected to the movable arm by a piece of twine and is held in tension by a rubber band as indicated at D. Electric current is passed through a controlling resistance coil and into the wire at the two connections. The instant current is applied, expansion takes place and the arm moves to the right. The changes that take place in this wire upon heating and cooling are illustrated by the heating and cooling curve on the right hand side of the figure. E = expansion and C = contraction. When the temperature of the wire reaches the decalescence point as indicated by the cooling curve, the arm stops and moves backward slightly, showing a contraction in the wire. When the transformation is completed, the wire again expands as indicated.

When the current is shut off, the wire cools and contracts. The arm moves to the left until the wire is cooled to the recalescence point, at which point a very pronounced expansion takes place. The arm moves forward through about  $2\frac{1}{2}$  times the movement that occurred at the decalescence point on heating. When this transformation is completed, the wire continues to cool and contract at its usual rate to room temperature. With a steel of such unusual strength we might expect that the arm would return to zero.

Contrary to our expectation, the arm does not return to zero, because the small rubber band has sufficient strength to stretch the wire while in a heated state. Refer to the strength curve in Fig. 96. In the author's opinion this curve indicates that the probable point of maximum weakness is the decalescence point. Hence, Fig. 148 shows the strength of the steel to be zero just at the  $A_3$  critical temperature.

*The Effect of Resistance to Expansion in Length*

The drawing Fig. 149 is a suggested shop experiment to demonstrate the above points. Any form of permanent resistance that will prevent expansion in the length of the test samples of

steel when heated will answer the same purpose. The block of steel must be of a strong steel and not a brittle casting or a piece of brittle steel which would rupture in the test. After the hole is cut in the block as indicated, fit in a piece of round stock as indicated at "b", being sure that the ratio of length to diameter is as 3 is to 1.

When ready, apply a gas or oil torch between the two points "d-d" and heat that part of the rod without appreciably heating any portion of block A. Let us consider what may happen. For the first 650 degrees Fahr., rod "b" will exert great pressure on

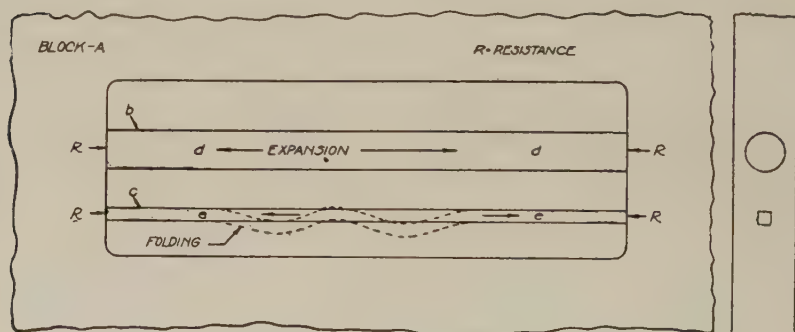


Fig. 149—Illustrating the Effect of "Resistance" to Lineal Expansion of a Heated Bar of Steel.

block A in its attempt to expand. During this expansion block A must have considerable strength or ductility to withstand this expansion. When the temperature of rod "b" reaches the point where it weakens, block A becomes active as a compressive tool and distortion takes place by upsetting rod "b". This continues with increase of temperature as rod "b" attempts to expand in length.

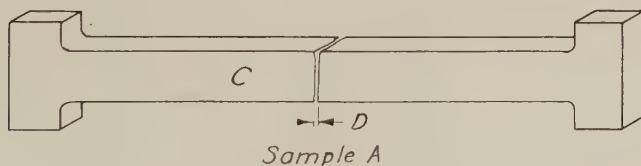
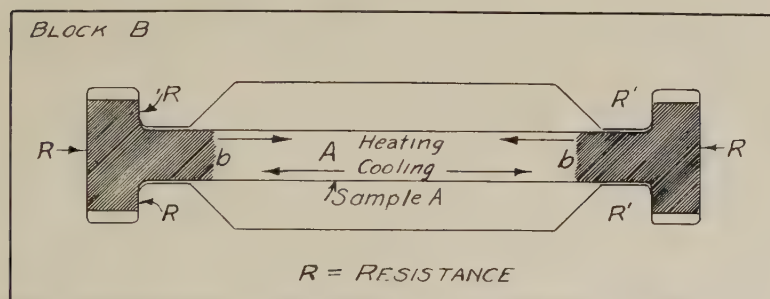
Let us assume that we have heated the length "d-d" to above the critical temperature and that the distance between these two points is 12 inches. The rod would have expanded  $\frac{1}{8}$ -inch in length if it were free, but due to the resistance of the block A it has been upset that amount. It would be well to remember that rod "b" is now filling the same space when hot that is occupied when cold.

If we allow rod "b" to cool, the metal will begin to contract or shorten in length. In doing so, it will fall out of the jig because

it must shorten  $\frac{1}{8}$  of an inch. The rod will shrink or contract to its normal deformed length because there was no resistance to prevent such contraction. When cold, it will be  $11\frac{7}{8}$  inches in length.

### *Distortion of thin Section*

If we place a small rod as indicated at C Fig. 149 and follow the same procedure of heating, etc., upsetting will not take place because of column weakness. Distortion takes place in the form of buckling or bending as indicated by the dotted line. If allowed to



THE SPACE D REPRESENTS AMOUNT OF DEFORMATION

Fig. 150—Illustrating the Effect of "Resistance" to Lineal Expansion and Contraction of a Heated Bar of Cast Iron.

cool slowly, the distortion or bending would remain permanent because there is no resistance to prevent the metal from contracting to its usual deformed length when cold. It is hoped this experiment has illustrated the disadvantage of local heating, unless there is an opportunity for the metal to expand freely.

### *The Effect of Resistance in Cooling of Metal*

The experiment outlined in Fig. 150 is a simple shop experiment that may be carried out advantageously by men in the metal

trades. Here again, any form of resistance to expansion and contraction will answer the purpose. Let us assume that a test sample of cast iron similar to A and having a ratio of length to width of 3 to 1 has been properly fitted and pressed into the block B. Apply a heating torch between the points "b-b". A study of the heating curve of cast iron indicates that it retains its normal strength with increased temperature up to 800 or 900 degrees Fahr. During that period of heating an unusual stress is applied to block B. When heating is continued, the strength of the iron decreases and distortion takes place by upsetting due to resistance of block B. This distortion continues as long as the temperature is increased, and as long as the metal attempts to expand in length.

Let us allow the casting A to cool slowly in the jig. Due to resistance  $R'$  there is no opportunity for the metal to shrink or shorten in length. At this point it would be well to study the process of cooling. Both of the dark areas on the end of "A" are supposed to be cold, consequently, cooling will progress from each end and toward the center of the casting. The exact center will be the last to cool, and the tension stresses will be concentrated at that point. It is well known that gray iron castings are inherently brittle and will not stretch, therefore rupture will take place quickly and in the weakest spot, the center. If allowed to remain in the jig after rupture and until cold, we will find a space between the ruptured ends. That space will be a fair criterion of the exact amount of distortion that originally took place in the iron castings. This is illustrated at D in view C.

Now ask an oxyacetylene or electric welder to weld the casting while in the jig. His efforts will be futile as long as the casting remains in the jig. There must be freedom for expansion and contraction to take place.

The writer once discussed the subject with a successful welder who made this statement: "Of course we couldn't weld a piece of cast iron in that condition, but if soft steel, it could be welded." Yes, it may be welded together, but what will be its condition of stress? To clear up this point, select any type of metal desired, preferably a piece of boiler plate. The plate of course could not be heated and upset in the jig on account of column weakness, but the plate might be heated between the points "b-b", and inserted into the jig while hot. When allowed to cool in the jig it will form

a problem similar to that of the cast iron except that it has not been upset. Owing to its ductility it will elongate or stretch and will not fail in the jig when cold. Let it remain in the jig until it is entirely cold, then tap it lightly with a hammer, and if it does not rupture, it will ring like a bell, evidence of being under great tension. A few hard blows might cause rupture. If broken, there will only be a small space between the ruptured points but under these conditions the space will not represent the real distortion that has taken place, as was shown in the casting. From this experiment one can readily see why localized heating causes stresses in metal, particularly when there is no freedom for expansion and contraction.

#### *Reduction in Diameter of Mass Due to Resistance*

The next illustration, Fig. 151, is suggested for aiding discussion of a factor that may be a contributing cause for failures in castings, boiler plates and machine parts. As in the preceding example, select a block of sufficient strength to prevent increase in diameter of test block "a". Drill a hole in block C into which a machined plug can be closely fitted. While the problem suggested is purely hypothetical, let us assume that it would be possible by some means to heat the plug without appreciably heating the block C. When first heated, the plug would increase in diameter in proportion to increase in temperature. If heated to 650 degrees Fahr. the plug would exert an unusual stress upon block C which, owing to its strength, would probably resist this stress. If block C were made of cast iron or hard brittle steel, rupture would undoubtedly occur. Upon further increase in temperature the plug would lose its strength and the resistance of block C would compress the soft plastic metal, distorting the plug. The metal in the plug must change its location and therefore would flow out of the ends of the hole as indicated by the hump in the side view of the block.

The heated plug would now occupy more space than it occupied when cold. What would happen to the plug if allowed to cool slowly? It would, of course, contract to its normal deformed dimension, and would be smaller in diameter but longer, as the resistance of block C would swage the plug and reduce its cross section. When cold the plug would not fit the hole.

This brings us to a phase of the subject that should be con-

sidered in the fabrication of all types of metal, especially where it is necessary to locally heat such parts or tools. The experiment with the plug illustrates a condition that frequently occurs in fabricating metal parts. Let us assume that block C in Fig. 151 is a solid block and that for some purpose it will be necessary to heat a spot the size of the plug at the center of block C in the manner

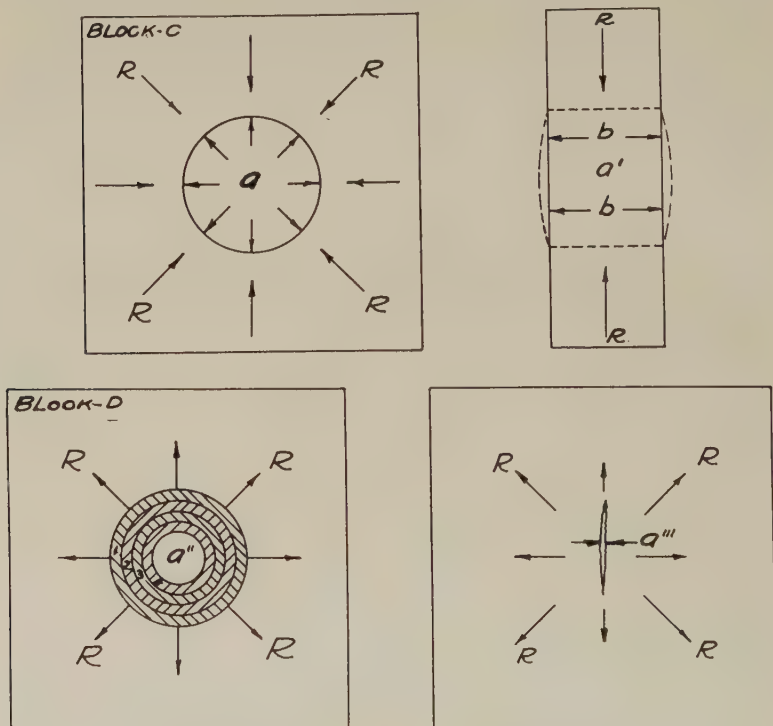


Fig. 151.—Showing Reduction in the Diameter of a Block of Steel Due to Resistance.

in which we attempted to heat the plug. The action and reaction of the solid will be identical to the occurrence in the plug. But, in cooling, we have an entirely different proposition from the shrinkage of the plug.

Before describing what may or may not happen in cooling, the following factors should be considered:

1. The metal is in an extended state, i.e., expanded to its maximum dimensions.

2. It is occupying about the same place in the block that it previously occupied when cold.
3. The heated portion is not free to shrink or contract similar to the plug.
4. The heated metal is united by perfect cohesion to the solid cold block; so what may we expect when the heated portion attempts to shrink to its normal deformed size?
5. Consider the order in which layers of metal at the center of the block will cool. We must naturally expect that the outside of the heated spot will cool first.
6. Let us imagine that the heated portion is about 12 inches in diameter. It must therefore shrink to about  $11\frac{7}{8}$  inches, when cold, but due to the resistance or pull of the solid block C, the metal must occupy about the same space cold that it now occupies in a heated state. Can we conceive of steel having an inherent quality of flexibility of adjusting itself to fit into the same space when hot as when cold? Unfortunately we cannot.

That we may have a clear conception of what occurs, the heated area of the block is divided into imaginary rings shown at block D. The outer rings will cool first and the direct center of block D will cool last; consequently, all of the pull set up by contraction of the various layers is concentrated upon the center, the portion last to cool. This leaves the metal under unusual tension or strain. If the heated metal happened to be a brittle gray iron casting or a piece of brittle steel, rupture would take place before the metal cooled to atmospheric temperature. If the block were iron or soft steel it probably would not rupture owing to the ductile properties of the metal. But, like our test in Fig. 149, it would be under unusual tension. If the block were boiler plate, it might pass inspection. Let us assume that this plate is placed in service and that due to some unusual stress it ruptures. The metal will crack open at the center as illustrated at "d". The opening in this crack will not be a criterion of the total amount of pull or deformation but it should indicate conclusively that distortion took place during fabrication of the material. Proper annealing would have caused a readjustment of such stresses throughout the entire plate if uniformly heated.



us see what will happen. The section A heats first. In doing so it expands in length up to about 700 degrees Fahr. without losing its strength. This will cause the bar to bulge in the middle as shown. On further increase of temperature the hot section becomes weak, but the resistance of cold section B prevents further extension in length, so the hot side upsets. By this time the cold section begins to expand and increase in strength and the metal takes the form indicated by the dotted line. The student is requested to stand the bar on edge so it will heat uniformly and when heated, to remove it from the furnace and allow the bar to cool slowly. When cold it will still be slightly deformed as indicated by the dotted line. In other words, the distortion is produced by the cold area which resists expansion of the hot and weak area.

To more clearly illustrate the effect of resistance in this form, local heating of a drop hammer die is shown at D. This drawing is the result of an actual occurrence. As is common in most industries, these dies were wanted in a hurry. A set was machined and finished as indicated by the drawing, heated quickly to a hardening temperature and quenched in the usual manner. Shortly after removing from the quenching bath both dies bursted, and there were four blocks in place of two.

Another set was immediately machined and when ready to heat for hardening the superintendent made the following suggestion: "Why is it necessary to heat the entire block, when all we want hardened is the surface and the depression in the face of the dies?" To the men, this seemed logical but how could this task be performed? An old furnace was available, so by blocking up the dies in the furnace, the top sides of the die blocks were heated. This may appear to be the ideal procedure but let us see what happened or what would happen in a similar case. The natural expansion must be cared for in some way.

The cold die was 36 inches long. If heat were applied to the surface as suggested, the middle portion of the die would then be 36 inches plus. The portion to be hardened must be heated above the critical temperature and therefore must expand  $\frac{3}{8}$  of an inch. In other words, when heated, the die should be  $36\frac{3}{8}$  inches in length. The question arises, how can soft and weak metal extend in length when connected by cohesion to an unyielding cold

body? The writer wonders if the reader ever saw a locally heated section of metal extended over the cold portion as indicated by the dotted section on each end of the die D? In other words, how can one conceive of a heated section being longer than the cold section when both are so united that any movement of one side must affect the other?

Careful observation of this condition indicates that the heated and cold section must form a perfectly straight line. On the first application of heat to the surface of the die it caused the center to bulge or hump as it tended or tried to extend in length.

As the temperature of the surface increased and the metal became weaker, the resistance of the cold area caused distortion in the form of upsetting. The heated section adjusted itself to the cold section, but both remained the same in length. It is understood of course, that there is no distinct line of demarcation between the heated and cold area as indicated in this drawing.

Let us now consider what happens in quenching such a die. In this case the die was lowered into a large tank of cold water agitated by compressed air. No provision however, was made for directing a stream of water to the portion of a die that should have been cooled first, consequently cooling began from the ends and progressed to the middle as illustrated by the cross hatched section at E. These areas cooled about in the order indicated and set, because of the resistance of the cold section. This created an excessive pull on the center portion of the metal which cooled last. When we consider that the heated surface must contract  $\frac{3}{8}$  of an inch in the hardening operation one can readily see the result of such a method of heating and quenching. Careful examination of the die after hardening showed that all of the pull was concentrated in the direct center, resulting in the crack, indicated at F. Singularly enough, the opening was exactly  $\frac{3}{8}$  of an inch, or the amount that the metal should have shortened in the cooling operation.

Another point to be considered is that in quenching a uniformly heated block, the cooling areas would compress the adjacent hot metal. But since the adjacent metal in this case was already cold the pull was in the opposite direction, as indicated.

From these facts one may see why the Safety Council will not allow the repair of small incipient cracks or defects in the lo-

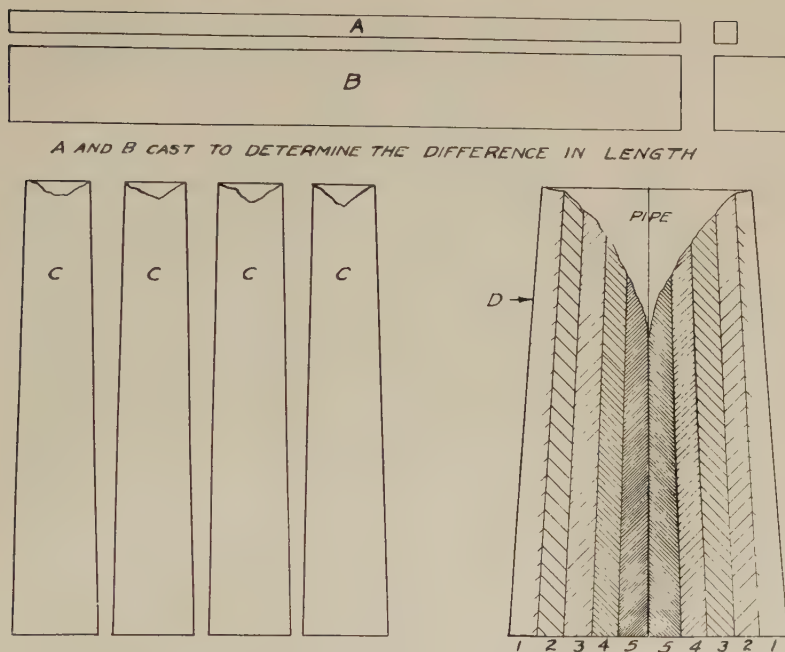


Fig. 153—Illustrating the Shrinkage of Castings and Ingots.

comotive reciprocating parts by means of an oxyacetylene or electric torch. This is also the cause of the separation of welded rail joints and other welds where there is not freedom of expansion and contraction.

### *Shrinkage of Castings*

If two pieces were cast in a sand mold, one 4 inches square and the other 1 inch square, both being of the same length when the metal was poured, what would be the difference in the length of these two castings when cold, provided that they were both poured from the same heat of metal and were allowed to cool under similar conditions? Such pieces are indicated at A and B, Fig. 153. According to the laws of physics, cross sectional area does not affect shrinkage in length. When cold, the bars will both be shorter, but the shrinkage in length will be equal and both bars will be of the same length.

The pipe formed in ingots on cooling is also termed a "shrink". To illustrate this point, four small ingots are shown at C. The volume of the pipe in the top of each ingot is proportional to the size of the ingot and is the same in each case. Instead of pouring the metal into the four small ingot molds, let us pour it into one large ingot and note the result of cooling such a mass. Why is it that there should be a greater shrinkage in a larger ingot or casting than in a small one? The writer feels the following to be the real reason. In the process of cooling, the outside or surface metal would cool first and shorten its length as indicated by zone No. 1 at D. As there is perfect cohesion between zones 1 and 2,—No. 2 being in a soft mushy state, it is upset by zone No. 1 due to the shrinkage of zone No. 1. When No. 2 reaches the temperature at which it develops sufficient strength and due to further shrinkage, it pulls No. 3 with it and so on toward the center. This; then, is evidence of distortion in the hot zone due to the compressibility of the cold zones and the shortening of the hot zones by shrinkage.

#### *Failure of Casting Due to Compressibility of Surrounding Cooling Areas*

The example next to be considered is taken from a very interesting problem, the cracking of a 900 H.P. Diesel engine cylinder head. These castings sometimes lasted five days or perhaps five years. The opening of the crack usually followed a cold shut formed in the cooling of the engine head.

Investigation disclosed the fact that the rupture was due primarily to the method of molding the casting in the foundry. By checking the cooling range between the extreme edge and the center where the crack usually developed, we found a variation in temperature of 700 degrees Fahr. The casting passed all inspection, but to determine whether the faulty portion of the casting was in compression or in tension, a cut was made along the path of former rupture.

That one may determine the cause without destroying an expensive casting, a simple experiment is outlined in the drawing, Fig. 154. A circular plate was cast horizontally and immediately upon solidification the cope and drag were removed and sand was shoveled away from the sides and off rings 1 and 2. Rings 1 and

2 were air-cooled and contracted quicker than the center, putting a compressive force upon the soft, mushy center and thereby causing distortion as in our experiment with the plug. The center section No. 4 being the last to cool, it was in tension similar

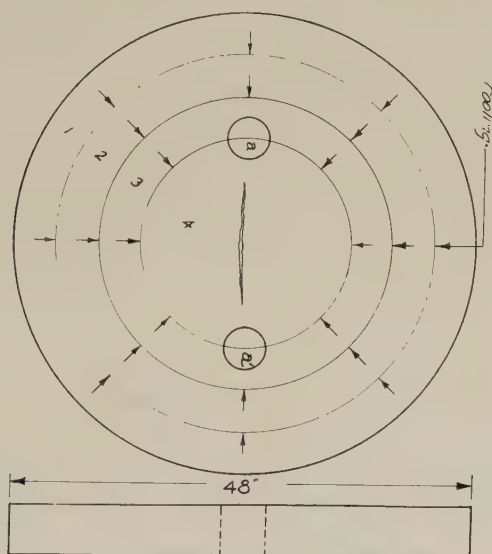


Fig. 154—Showing a Round Plate-Like Casting to Illustrate Certain Shrinkage Problems.

to the previous experiment. If the casting has not cracked from this drastic operation it will be under such tension that the least stress may cause rupture. If the experimental casting has not failed under this treatment take the casting to a planer, and using a quarter inch parting tool, cut a slot between the holes *a* and *a'*. If the casting is in tension you will be very much surprised by the result of the test. In our investigation of the Diesel engine head we found by a similar test that the slot opened 0.025 inches of its own accord, a sufficient amount to let water out.

A chill was applied in an attempt to correct this condition, but with poor results. Another tool test was made by attempting to cut a slot with a  $\frac{1}{4}$  inch parting tool, but we had to grind 13 thousands of an inch off the parting tool before we could succeed in penetrating through the casting. The compressed metal resisted

tooling. This was self evidence that the metal was in compression rather than in tension. The solution of such problems was the regulation of cooling or chilling to secure a uniform rate of cooling in all parts of the casting.

### *The Compressibility of Adjacent Cold Metal*

Warpage and cracking frequently occur in castings, as illustrated by Fig. 155 which represents the molding of a rectangular casting at C. Upon solidification of the casting the cope is removed

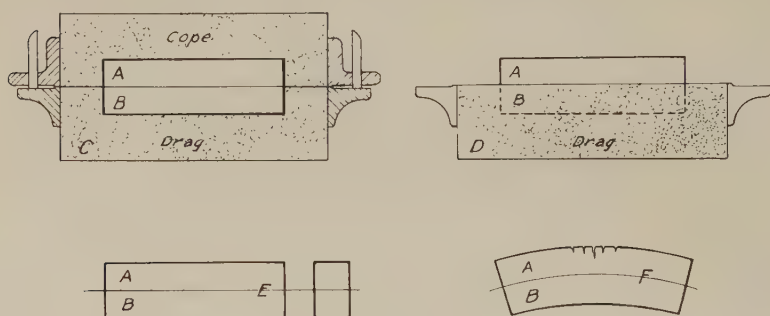


Fig. 155—Showing the Effect of Removing the Cope of a Mold to Produce Rapid Cooling.

as indicated at D and the upper half of the casting allowed to air cool. This problem is similar to that of the drop hammer die. The cool side A upsets the hot side B while the metal is in a soft, mushy state. When B cools to atmospheric temperature, it will contract and bend the casting as shown at F, since upsetting has limited its final length to less than normal. Checks or cracks may occur in the chilled side, as shown on side A. If the casting had been cooled slowly and uniformly in the mold, it would come out straight as indicated at E. This example is taken from actual practice.

### *Pipes and Shrinks in Castings*

The centers of large masses of cast iron or steel are not as sound as surface material, due to shrink cavities or pipes. Impurities that melt at a lower point tend to segregate in spots at the center. The center pipe is more or less spongy and open. These conditions are more or less contributing causes to the weakness of castings.

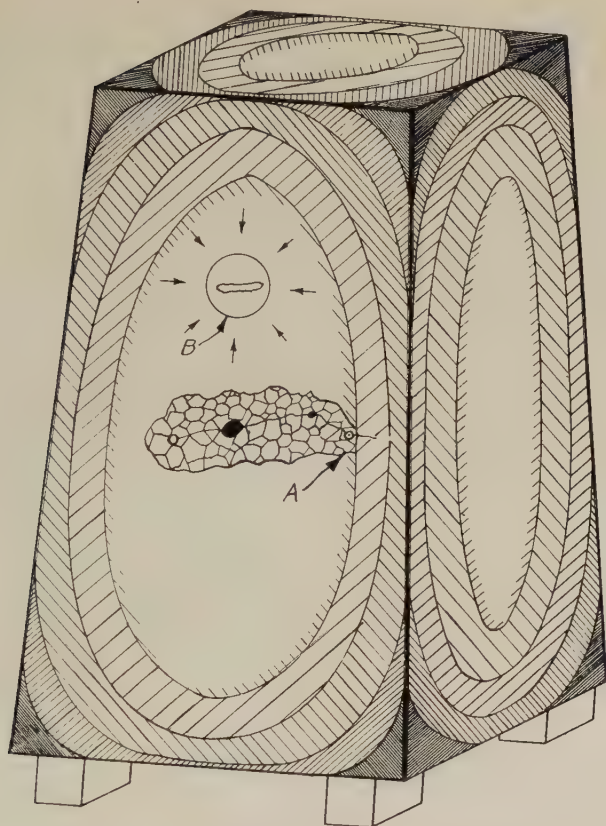


Fig. 156—Illustrating Possible Cause of Internal Defects in Annealing a Large Casting.

When such castings are put into service there is a possibility of an internal failure beginning from these points of weakness since such a defect would cause a discontinuity in the metal, reducing its tensile strength in proportion to the size and number of internal defects or discontinuities.

#### *Annealing of Piped Castings*

Let us now consider the annealing of castings containing these inherent weaknesses at the center. Fig. 156 shows a fair sized hammer block. It is placed upon supports as shown, to allow the heat to circulate freely around it. In heating, the heat is, of course, greatest at the outside of the block. The intensity of

the heating zones or areas is indicated by the dark and heavy shading at the corners which diminishes in intensity towards the center.

It would be well at this point for the reader to refer back to curve, Fig. 96 which shows the strength of metal at elevated temperatures. If this block were made of cast iron, it would maintain its normal strength with increase of temperature up to 800 degrees Fahr. at which point there would be a slight increase in strength. The writer feels that damage will occur at this temperature if it is to occur at all. Conceive of the outer layers of the material expanding in length away from the center, each at a different rate. The surface layers expand at a faster rate than the defective center. Is it not conceivable that at least a minute rupture may start from a slag inclusion or internal shrink as at A, resulting from the release of excess stress induced by the uneven expansion of adjacent layers of metal? Such a microscopic rupture may increase under further stress, following a zig-zag path across the mass through other weak spots and resulting in a serious crack as shown by the path at A through internal defects.

If the greatest source of weakness at the center is longitudinal rather than horizontal, then is it not also conceivable that due to the expansion at each end of the block, an internal rupture may start and grow, causing the block to split lengthwise? There may be no surface indication of such a rupture but still the rupture may grow by strain caused in service and result in failure. The more rapidly the heat is applied, the greater the force exerted and, consequently, the greater the danger of internal rupture. Therefore, heat slowly and uniformly.

### *The Effect of Repairing Surface Defects*

To illustrate this point we have drawn an imaginary defect on the surface of this casting as indicated at B, Fig. 156. The repair of such a defect is usually delayed until the casting has cooled to atmospheric temperature. Consideration must be given to the resistance of the surrounding cold metal when attempting to weld this defect.

### *The Effect of Forging Upon Internal Defects*

Let us now assume that the cast block, Fig. 156, represents



Fig. 157—Photograph of a Steel Bar Which Failed Due to Fatigue. Note the Internal Rupture to the Left of the Section.

a large ingot of steel, (the general shape, of course, is not correct). Similar defects may develop on reheating the ingot for forging. A microscopic rupture may be developed in the interior. An ingot is usually reheated to a forging and not a welding heat, the latter being the higher temperature. Let us reduce this ingot in cross section under a powerful hydraulic press. In reducing the cross section, particularly when the metal is not at a welding heat, is there not danger of forming further discontinuity in the minute rupture? In other words, would it not be possible to cause the rupture to grow? Failure might look like the ruptures shown in Figs. 157 or 158 which both show evidence that an internal rup-



Fig. 158—Two Views of a 12-Inch Steel Bar That Failed Due to Fatigue. Note the Internal Rupture at the Bottom of the Right Hand View.

ture was the root of the ultimate fracture.

The writer believes that it is well to digress from our original discussion and touch on the cooling of castings after annealing. If massive castings are to be annealed, why is it necessary to allow such castings to cool to atmospheric temperature after pouring, and then to reheat them? As previously stated, the writer believes it is well understood that no structural change takes place in the metal below 1290 degrees Fahr. Then why not conserve the original heat and prevent many of the disastrous conditions above described, by placing the casting in the annealing furnace while hot? If surface repairs are necessary, why not repair the metal while it is hot? These repairs would then be annealed and much heat energy would be conserved.

#### *Shortening of Length by Repeated Heating and Cooling of Steel*

Certain allowances for shrinkage must be made in the hardening of taps, reamers, etc. Such tools shorten their length with a slight increase in diameter, because of the customary method of quenching tools and other material in water with the hope they will cool uniformly throughout, all at the same time. Unfortun-

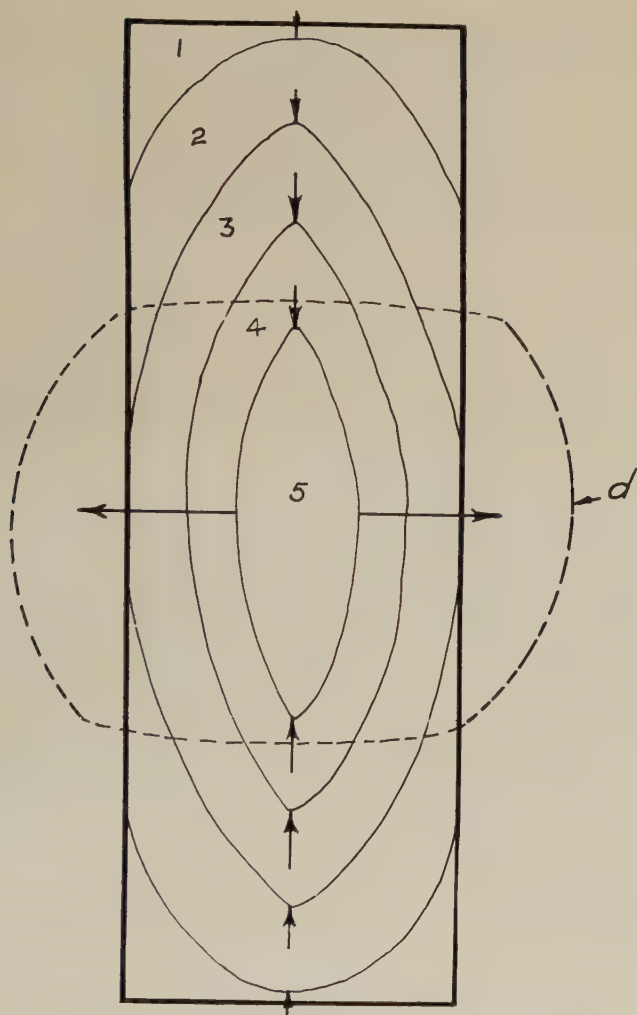


Fig. 159—Diagram Illustrating the Shortening of the Length of a Bar of Steel Due to Repeated Heating and Cooling.

ately, this is not true and such treatment cools the tool from the ends and toward the center. By a process of jig and spray quenching, the heat can be removed first from the surface adjacent to the center of the tool. The writer feels that this process will do away with much shrinking during quenching. Fig. 159 shows that

repeated heating and cooling of steel will shorten its length with a corresponding increase in diameter. When steel is heated above the critical temperature, the metal is in an expanded state and when quenched, the ends cool first. The figure shows a cylindrical piece of steel divided into imaginary cooling rings, numbered 1, 2, 3, 4, 5. When this metal is plunged into water, ring No. 1 on each end will cool first, and the others in the order indicated. In cooling, these rings must shorten in length, consequently, they exert a compressive stress on the adjacent heated portions. The center being the last to cool, the force is concentrated at the weak point in zone No. 5. The hot central portion of the cylinder is the least resistant to force, and if repeatedly heated and quenched a sufficient number of times, the metal will assume the form of a sphere as indicated by the broken lines at D, regardless of the original shape of the piece.

In presenting this phase of the subject to a group of industrial men, one man took exception to the statement that regardless of cross section it would become a sphere. To prove or disprove the statement he selected a rectangular section as indicated at "a" Fig. 160. He was surprised to find that as the metal became shorter, it began to bulge out on the two weaker sides of the rectangle, as at "b." This bulging is clearly indicated by two other similarly treated blocks, "c" and "d." After heating and quenching 350 times, it assumed a nearly perfect sphere, as indicated at "b." A partial record of the shortening of length with increase of other dimensions is outlined in Table IV.

**Table IV**  
**Dimensions of a Specimen of Low Carbon Steel After Heating and Quenching from Above the Upper Critical Point 350 Times**

	Original Size	1	2	3	4	5	6	7	8	9
Length	2.500	2.497	2.492	2.489	2.486	2.484	2.480	2.475	2.470	2.467
Width	2.000	1.997	1.996	1.994	1.994	1.994	1.992	1.990	1.990	1.990
Thickness	1.312	1.319	1.325	1.333	1.339	1.350	1.357	1.368	1.373	1.378
Quenched	10	15	20	25	35	45	60	100	150	250
	2.465	2.447	2.420	2.400	2.372	2.348	2.318	2.357	2.315	2.258
	1.990	1.987	1.983	1.985	1.989	1.993	1.999	2.033	2.086	2.118
	1.382	1.439	1.482	1.511	1.612	1.662	1.754	1.920	2.037	2.120
Quenched	300	325	335	350						
	2.228	2.216	2.215	2.207						
	2.145	2.167	2.167	2.170						
	2.170	2.204	2.207	2.224						

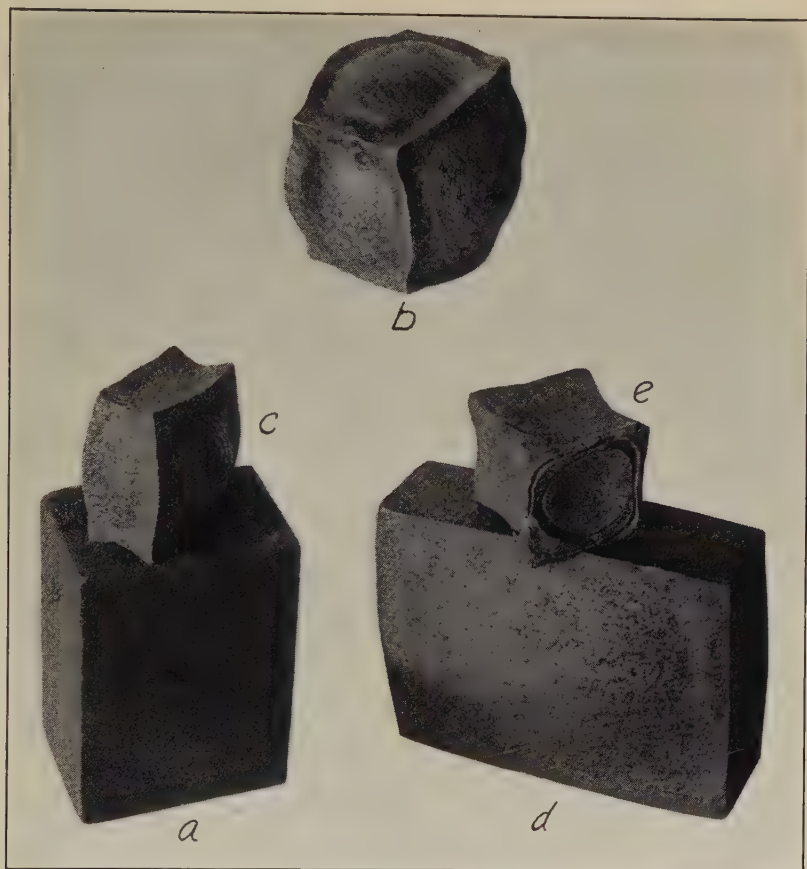


Fig. 160—Photographs of Rectangular Blocks of Steel Which Have Been Repeatedly Heated and Quenched.

Later the young man decided to experiment upon a square section of oil-hardening steel, to determine the cause of its non-deforming qualities. After heating and quenching the block 125 times, it took the form as indicated at "e". The writer believes that the metal took this form because of the strength of the fine-grained structure of deformation resisting steel.

To further emphasize this point the writer takes pleasure in mentioning the result of a similar experiment carried out by F. C. Lau of Chicago. He took the time and patience to heat and quench a piece of tool steel  $1\frac{1}{2} \times \frac{1}{2} \times 3\frac{1}{2}$  inches 450 times. Finally

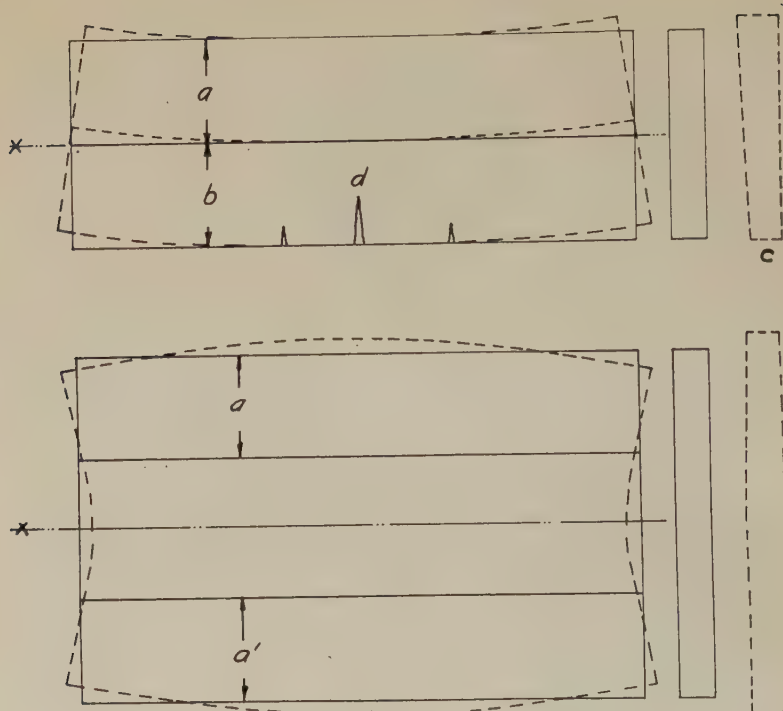


Fig. 161—Illustrating Warpage Due to Unequal Cooling.

it assumed the shape of a little foot ball. In all the reheating and quenching of this high carbon steel the sample did not show a crack. It is self evident that it took considerable time and patience to heat the block slowly and uniformly before each quench.

### *Deformation, Warpage and Cracking Due to Local Cooling*

It has been clearly demonstrated that if all the precautions were taken to heat a section of steel and if it were quenched uniformly, it is very probable that no deformation or warpage would take place except the shortening of its length. If the piece be immersed in the quenching solution in such a manner that part of it cools more rapidly than some other part, one may expect local distortion, warpage, and probably cracking, depending upon the type of steel at hand. The following experiments are offered to prove these statements. The first experiment is outlined in the

upper drawing, Fig. 161. The rectangular section is uniformly heated and the lower section "b" up to "x" is cooled in water and held in that position until the hot portion "a" (remaining out of the water) turns black. Upon examination the reader will find that when cold it takes the form similar to the dotted line. If the reader desires to carry out this experiment, use for the first experiment a piece of soft steel about  $\frac{1}{4}$  inch by 2 inches by 6 inches, being careful to square the ends so that the block may be accurately measured. Heat and quench the block in water as above indicated and, when cold, again check its dimensions.

For the second experiment select a piece of automotive spring steel if available and if not, use a piece of carbon tool steel of about the same dimensions as above described and repeat the above experiment. The tool steel will assume the same general shape as that of soft steel. If the steel does not crack as indicated at "d" the metal will be under such terrific tension that a slight blow of the hammer may cause rupture.

Now select a wider section as indicated in the lower drawing Fig. 161 and quench the two sides, "a" and "a'" by alternately immersing them in water. When cold this piece will assume the form of the dotted line. This will demonstrate why metal takes the form of a sphere, why it always bulges in the middle and why it becomes hollow on the end when heated and quenched.

The photograph Fig. 162 is the result of the first and second experiment, except that the soft steel "a" was heated and cooled a number of times to distort it.

To more clearly interpret the changes that take place, a drawing, Fig. 163 is shown. The rectangular section C is assumed to be exactly 12 inches in length when cold. When heated above the critical temperature it expands to  $12\frac{1}{8}$  inches as indicated on the neutral axis line X. Let us assume that we are cooling the lower half B in water up to line X. When cold this section will shrink or contract to its normal length, 12 inches.

How long is the hot section "A"? Many men answer that the hot side is still  $12\frac{1}{8}$  inches long while hot. Experiments of this character demonstrate that the hot and cold sections are of equal length.

But what happened? The section B contracts while cooling

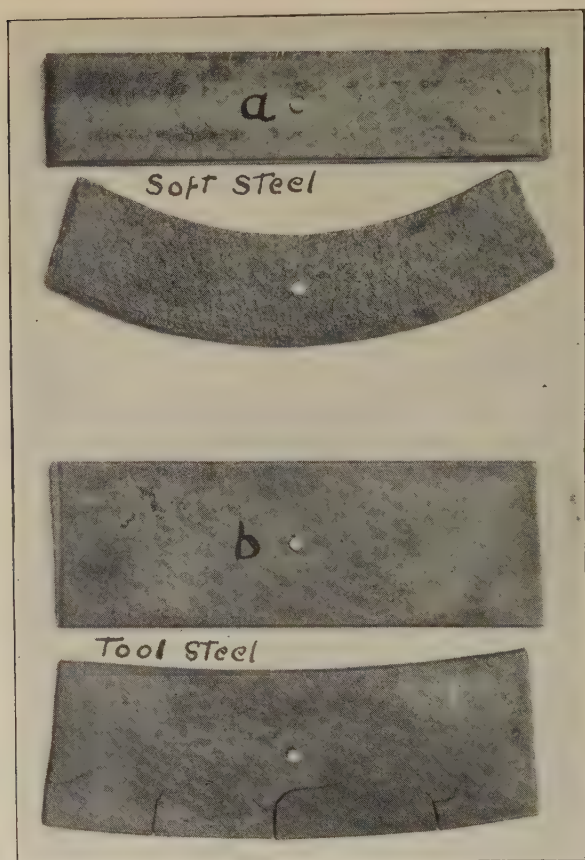


Fig. 162-- Showing Warpage and Cracking Due to Cooling Lower Half of "a" and "b".

rapidly and in its effort to return to normal length, it pulls the hot side with it, clear evidence of compressive distortion as outlined in our experiments.

One side of the metal is cold and the other side is hot. When the heated side cools to atmospheric temperature it must shorten its length by shrinking. Therefore, if the lower section B shortens  $\frac{1}{8}$  of an inch in cooling, A must be  $\frac{1}{8}$  inch shorter when cold, and that is exactly what happens. If one side of a piece of metal is shorter than the other side, it must bend or warp as indicated at D. This condition may be traced to the distortion of metal when

deflected from a straight line in the form of a bend. The neutral axis X does not change its length. The metal on the inside of the arc compresses and increases in cross section, while the metal on the outside elongates and therefore decreases in cross section, clear evidence of distortion.

In some of our soft structural metal this action seldom causes cracking but it induces stress. Let us determine why a piece of tool steel cracks. If a test bar of tool steel in the hardened state,

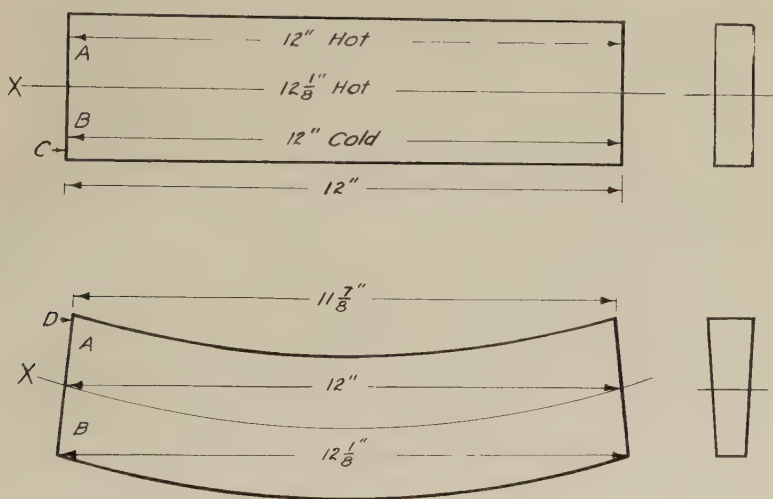


Fig. 163—Diagram Showing the Cause of Deformation and Warpage Due to Local Heating.

similar to the cracked portion of the above experiment, was pulled in a tensile testing machine it would show very great strength with no appreciable elongation or ductility. On the other hand, if a similar test bar is supported on two points and pressure applied in the middle in an attempt to bend the bar, there may be slight deflection but rupture will occur quickly. In shrinking, the heated section of the tool steel acts in a similar manner except that it pulls up on both ends and usually cracks. If it does not crack, it is under such great tension that a slight hammer blow or stress will cause rupture.

From the above experiment we can now trace some of the difficulties encountered by the oxyacetylene and electric welder and the reason for the instruction that a definite opening be left on

the ends of two plates to be welded together. The open space is to take care of crawl or shrinkage. Fig. 164 illustrates the compressive action of the part of the weld at A in shrinking or contracting to its normal state. In doing so it compresses the soft

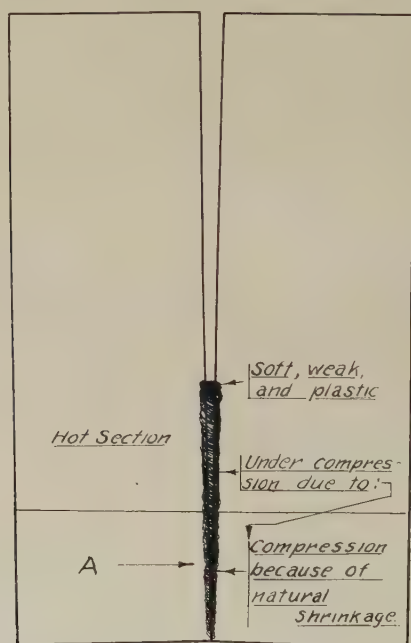


Fig. 164—Illustrating the Shrinking of a Butt Weld.

plastic metal above it. The opening at the top closes as the weld cools. It is not reasonable to assume that when two pieces are tacked together, a similar distortion takes place leaving stresses in such parts? This should emphasize the disadvantage of going over a weld to correct any imperfection that may have been missed along the line.

### *Causes of Heat Cracks*

The heat cracks in drop forge and other types of dies where heated metal comes in contact with the die are very serious and costly. As a rule the the real cause is not well understood. In explanation, let us consider the effect of the resistance of the cold

die to extension in length when the edges or projections of a die are heated to a temperature where such resistance would cause permanent distortion. It is often assumed that the rapid quenching of a heated die will prevent heat cracks. If the die attains a temperature where distortion has taken place, all the quenching

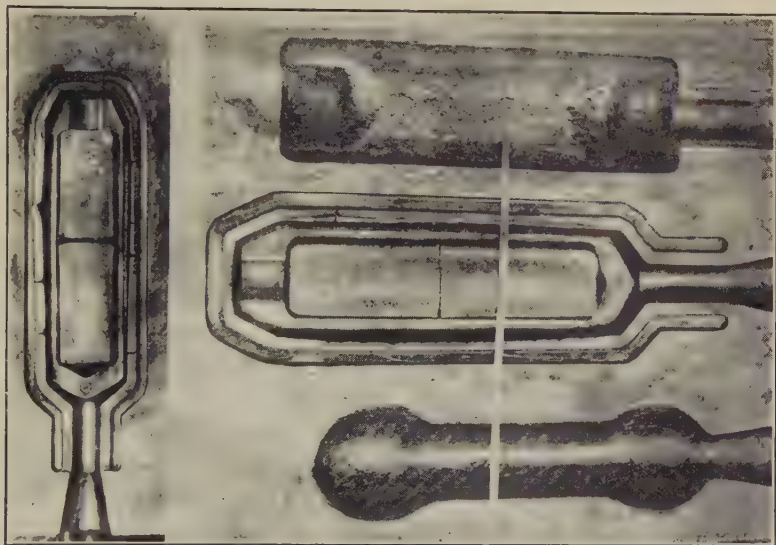


Fig. 165—Showing Heat Crack in an Expensive Die as the Result of Allowing it to Become Too Hot During Forging Operations.

in the world will not prevent cracks. Let us examine the cause of the heat cracks in photograph Fig. 165. This is an unusually large die and appears to have some exceptionally sharp corners. When these corners are heated, by contact with the heated metal in forging work, they must extend in length. Where is the metal going to? The corners cannot extend in length. If the temperature is right, distortion takes place and on cooling the metal attempts to return to its normal position. If quenched quickly, a slight notch, abrasion or defect will immediately cause rupture. This is further aggravated each time the metal is heated and cooled in forging a piece of metal. How can this be prevented? There is only one preventative. Never, under any circumstances, allow the die to become hot enough to cause distortion. Once this has occurred, there is no possible method of correcting the trouble.

While this process of distortion has many disadvantages as above outlined, it has some advantage in the correction of previous mistakes. Take for an illustration a bushing in which the hole is too large. Let us attempt to close a hole in a bushing, hob or gear made of steel that will withstand compressing. Devise some scheme to prevent the quenching solution from making contact with the portion of the metal that is to be shortened or made smaller in di-

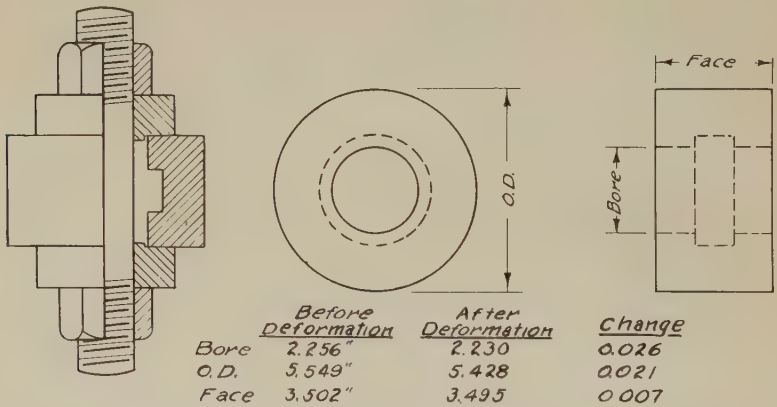


Fig. 166—Illustrating the Inward Expansion of an Oversized Hole in a Gear Blank.

ameter. The following is taken from an experiment carried out as a result of the suggestion at one of these lecture courses. The object was a large cast steel gear which the writer felt would stand quenching.

Rather than carry out an experiment on the large and expensive gear, a similar cross section was made on a smaller scale, as indicated in drawing, Fig. 166.

A large quantity of small gears opened up 2 to 4 thousandths of an inch on quenching. These were reclaimed by making a bolt slightly undersize, placing 12 of these gears on the rod with a washer on each end, then heating and quenching them. As a rule, the two end gears would not close a sufficient amount, due probably to too rapid quenching on each end. Ten of the gears reclaimed by this process would close the desired amount and were reclaimed.

*Answer to Warpage Problems*

The reader has probably been wondering when the answer would be forthcoming to the problems suggested on the first two figures shown in this lecture. The author does not believe it is necessary to go into detail to answer these problems. They were fully explained in the various suggested experiments. The reader may relieve his mind of many complications in the solution of industrial heating problems. The solution of all such problems may be answered in a few words—Always remember that *the hot side will be the short side when cold*.





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